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Aerospace Report No.
ATR-78(3818)-1ND

MARAD/GPS DEMONSTRATION PROJECT
PHASE I REPORT

Prepared by

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Global Positioning System Directorate

September 1978

Satellite Systems Division
THE AEROSPACE CORPORATION
El Segundo, Calif. 90245

Prepared for

U.S. DEPARTMENT OF COMMERCE
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This report provides an overview of Navstar GPS operation and develops the demonstration objectives and data requirements for the at-sea demonstration of the z-set. It develops the rationale and illustrates the engineering analyses that went into the suggested z-set hardware changes and demonstration software requirements. This report also defines the z-set error sources, describes the ship simulation used to predict z-set performance, and discusses the simulation results. It includes recommendations for the demonstration configuration and identifies a potential

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20. GPS impact on marine systems of the 1980's as an area for future investigation.

Aerospace Report No.
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MARAD/GPS DEMONSTRATION PROJECT
PHASE I REPORT

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FOREWORD

In March 1976, the Global Positioning System (GPS) Joint Program Office (JPO) accepted the responsibility for planning a civil maritime demonstration of the GPS Z-set for the U.S. Department of Commerce, Maritime Administration (MARAD). This Phase I report is in partial fulfillment of the Maritime Administration/Navstar Global Positioning System (MARAD/GPS) Demonstration Project. This report provides a comprehensive overview of the engineering studies and analyses performed by The Aerospace Corporation.

For the MARAD/GPS Demonstration Project, the MARAD Program Office provides overall project guidance and gives approval for the major tasks and milestones. This office is headed by Mr. C. Mathews, Program Manager, assisted by Mr. J. Walsh and supported by Mr. J. Fee, of the MITRE Corporation, its systems engineering contractor. For the Space and Missile Systems Organization (SAMSO), Maj. D. Dostaler manages the MARAD/GPS Demonstration Project and directs the support of its general systems engineering contractor, The Aerospace Corporation. Mr. E. Lassiter, Principal Director of the Satellite Navigation System Directorate, heads the MARAD project effort for The Aerospace Corporation in support of the GPS JPO. He has assigned the project engineering responsibility to Mr. J. Pitre under the direction of Mr. P. Jorgensen, Director of the Systems Studies Office.

Funding for this effort was processed through SAMSO (Air Force Systems Command) Contract No. F04701-77-C-0078 under an interagency agreement.

ACKNOWLEDGMENTS

This study required various technical disciplines for its execution and relied on the efforts and support of many members of The Aerospace Corporation's technical staff. The principal contributors were:

Harold Bernstein	Demonstration objectives and data requirements
William P. Blair	Z-set errors, simulation, and ship navigator
Sydney W. Lewinter	Z-set antenna and front-end requirements
Darrell A. Schermerhorn	Operating system and software task
Keith H. Senechal	Display presentation and emulation

Other contributors include: R. Constant, computer and equipment interfaces; P. Jorgensen, GPS constellation and Phase I satellite coverage; J. LaFrieda, navigation algebra; M. Power, demonstration equipment; E. Skomal, atmospheric and multipath analyses; R. Thompson, display surveys; R. Tow, Z-set hardware; and K. Young, user tapes.

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1. INTRODUCTION

This report highlights the engineering studies and analyses performed to define the requirements of the at-sea demonstration for the performance evaluation of the Navstar Global Positioning System (GPS) Z-set. This Z-set demonstration will provide the necessary data for the Maritime Administration (MARAD) to assess the GPS potential in improving the competitive status of the U.S. flag fleet.

1.1 PROGRAM OVERVIEW

The MARAD GPS Demonstration Project is a two-phase program funded by MARAD and under the management of the JPO to analyze and plan a civil maritime demonstration of the Z-set. Phase I of the program covers the design and analyses, and Phase II consists of the demonstration and data evaluation. The task plan developed from MARAD's work statement specifies the following Phase I tasks:

- Define the demonstration objectives and data requirements
- Specify the demonstration configuration
- Identify the hardware modifications and software additions required to optimize Z-set performance in civil maritime applications
- Determine the satellite coverage over the ship routes of interest
- Identify the Z-set error sources

In Phase II, the preparation, installation, and execution of the at-sea demonstration will be implemented by the integration contractor (possibly the Magnavox Advanced Products Division,

builders of the Z-set) under contract to MARAD. The planned SAMSO/Aerospace role for Phase II provides for the technical direction and monitoring of the integration contractor to ensure compatibility with the ongoing JPO development efforts for user equipment.

The MARAD/GPS Demonstration Project will provide performance credibility to the maritime community by comparing Z-set performance with that of other marine navigational aids. The equipment configuration selected for the demonstration permits automatic data recording and transmission. It also performs dead reckoning navigation with inputs from the ship's log and gyrocompass between periods of no satellite coverage. The shipboard display, specifically designed for the demonstration, allows operator entries for initialization and display requests and automatic reinitialization after periods of no satellite coverage.

1.2 ASSUMPTIONS

The Phase I engineering studies and analyses were performed to a baseline equipment configuration mutually agreed on by MARAD/MITRE and SAMSO/Aerospace. To retain Z-set performance integrity, the engineering work was performed assuming that no Z-set software changes would be requested; any additional software functions would be part of the demonstration software package. A similar assumption applies to the Z-set hardware, though not to the easily replaceable assemblies that are application-dependent (e.g., the antenna, preamplifier, and display).

1.3 SYNOPSIS

This report provides an overview of Navstar GPS operation and develops the demonstration objectives and data requirements for the at-sea demonstration of the Z-set. It develops the rationale and illustrates the engineering analyses that went into the suggested Z-set hardware changes and demonstration software requirements. This report also defines the Z-set error sources, describes the ship simulation used to predict Z-set performance, and discusses the simulation results. It includes recommendations for the demonstration configuration and identifies a potential GPS impact on marine systems of the 1980's as an area for future investigation.

2. NAVSTAR GPS OVERVIEW

Navstar GPS is a multiservice Department of Defense program designed to meet the requirements of the armed forces in the 1980's and beyond. This overview describes GPS system concepts and performance for commercial users. Unless required for technical accuracy or clarity of exposition, system features and characteristics intended for military use are omitted.

Navstar GPS is a satellite-based radio navigation system operating at L-band that will provide commercial users located on or near the earth's surface with position and velocity information accurate within 100 to 200 ft and 1 to 2 ft/sec, respectively (assuming one-sigma errors (Sec. 6.2) and favorable satellite geometry). Once the GPS system becomes fully operational in the mid-1980's, continuous navigation will be possible at any time of day and throughout the world. The GPS system consists of three major segments:

- The space segment, which broadcasts satellite position and system time
- The user segment, which processes the information from four satellites to determine position and velocity
- The control segment, which tracks the satellites and obtains daily updates of their ephemerides and estimates of the system time bias

Figure 2-1 depicts the multiple aspects of the Navstar GPS system being pursued during Phase I. During this phase, six satellites will be launched from Vandenberg AFB and controlled in orbit by the Air Force Satellite Control Facility (AFSCF) and the master control station (MCS). Three satellites are already on-orbit. Initial user simulation tests are being conducted at Yuma Test Site, and later this year these tests

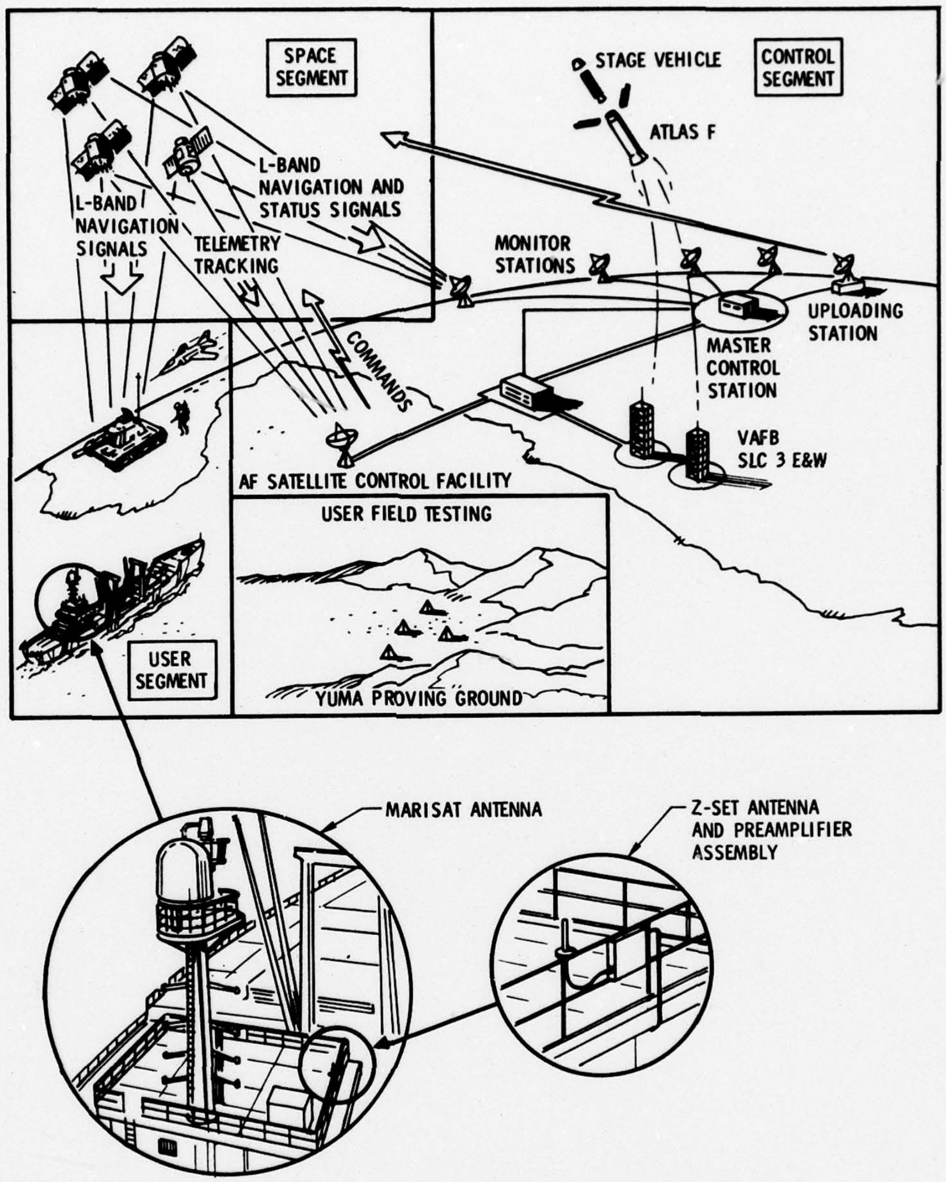


Fig. 2-1. GPS Phase I Overview

will be with the satellites on-orbit broadcasting navigation signals.

2.1 GENERAL SYSTEM CONCEPT

Direct-sequence spread spectrum systems, through their property of coded modulation, provide high-resolution ranging by employing high code rates. GPS employs a direct-sequence spread spectrum system to achieve its high-resolution range measurements. (Direct sequence refers to the high-speed pseudo random noise (PRN) code rate sequence used to modulate the L-band carrier.) For commercial users, the code has a 1.023-Mbps bit rate and repeats every millisecond. Figure 2-2 is a simplified block diagram of a direct-sequence system that conceptually represents the GPS navigation system. The L-band carrier is modulated by the PRN code generator. The modulation power spectrum produced is $(\sin x/x)^2$, with the mainlobe bandwidth equal to twice the code rate. The receiver reconstructs the carrier by matching a locally generated PRN code sequence to the incoming code embedded in the carrier. For high-resolution range measurements, the receiver correlates its internally generated signal with the received signal to within 0.1 bit. Hence, for a code rate of 1 Mbps, ranging accuracies of less than 100 ft may be achieved.

In addition to high-resolution ranging, spread spectrum systems provide interference rejection (anti-jamming margin), minimum interference with other systems, and code division multiplexing. Interference rejection occurs as a result of the spectrum spreading in the transmitting process and the consequent despreading necessary in the operation of spread spectrum receivers. The ratio of the spread to the rate of the information sent is called the process gain. The interference rejection is determined by the system's process gain

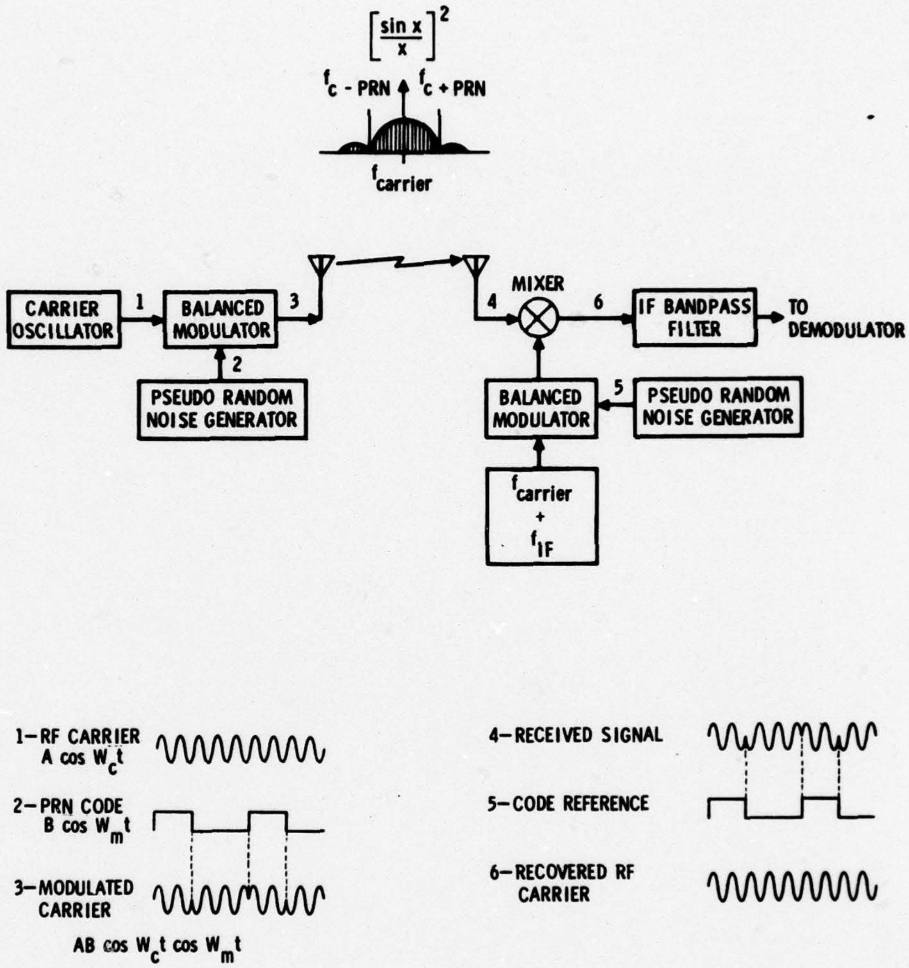


Fig. 2-2. Block Diagram of Direct-Sequence Spread Spectrum System

less an acceptable signal-to-noise ratio output and the implementation losses. For commercial users of the GPS navigation system, this margin (sometimes called the anti-jamming margin) is about 25 dB. Since spread spectrum modulation results in wideband, low-power-density signals with statistical properties similar to random noise, the transmitted signal is not readily detected. As a corollary, spread spectrum systems provide minimum interference with other systems. Code division multiplexing provides multiple access since it allows transmitters to operate simultaneously on the same frequency by employing different code sequences.

2.2 SPACE SEGMENT

In its operational configuration, the GPS satellite constellation will consist of 24 satellites deployed in three orbit planes, eight satellites per plane. The orbits are circular with an inclination of 63 deg and an altitude of 10,900 nmi. This constellation ensures that at least six satellites are in view from any point on earth, thus giving coverage redundancy and worldwide three-dimensional position and navigation capability. The six satellites to be deployed in Phase I will provide a symmetrical pattern over the Yuma Test Site once each day. A cluster of three or more of the six satellites will be visible at Yuma for more than seven hours each day. The GPS orbits have a period of 11 hr and 58 min; thus, the deployment pattern as seen by an observer from a fixed location on earth shifts east with each successive appearance at the rate of about one degree per day.

2.3 CONTROL SEGMENT

The control segment consists of four monitor stations, an upload station, and the MCS. The monitor stations are

located at Hawaii; Elmendorf AFB, Alaska; Guam; and Vandenberg AFB, California. The monitor stations are unmanned data correlation sensors under the control of the MCS for gathering local meteorological data for tropospheric signal delay corrections at the MCS. The upload station located at Vandenberg AFB provides the communication interface between the control segment and the satellites. It utilizes S-band telemetry command and control to update each satellite with the navigation data required by the user. The MCS, also located at Vandenberg, directs the entire control segment operation. It performs the computations necessary to determine the satellite ephemeris and system time bias, generates satellite upload of user navigation data, and maintains bookkeeping on all satellite contents and status.

2.4 SIGNAL STRUCTURE

Each satellite transmits two spread spectrum PRN navigation signals, one at 1575 MHz and a second signal at 1227 MHz. The L_1 (1575 MHz) signal is a composite waveform consisting of a precision (P) signal and a coarse acquisition (C/A) signal transmitted in phase quadrature. The P signal provides precision navigation for military users. The C/A signal aids acquisition of the P signal and serves as the navigation signal for military and commercial users. Both the P and C/A signals are biphase-shift-keyed continuous rf carriers with embedded system data at a 50-bps rate. The system data include satellite ephemeris, time bias, and atmospheric delay correction and will be updated once per hour when the system becomes operational. The PRN chipping rates are 10.23 Mbps for the P code and 1.023 Mbps for the C/A code, with respective code lengths of seven days and one millisecond (the short C/A code allows rapid acquisition of the P signal). Each satellite transmits a unique set of PRN code sequences, which allows all

satellites to transmit on the same carrier frequencies. The L_2 signal carries the P code only and allows the high-precision military user to make atmospheric time delay measurements. The constant envelope L_1 signal is of the form

$$S(t) = \sqrt{2P_p}\, P(t) \sin 2\pi L_1 t + \sqrt{2P_{C/A}}\, C(t) \cos 2\pi L_1 t$$

where

P_p = P signal carrier power
$P_{C/A}$ = C/A signal carrier power
$P(t)$ = composite P signal = ± 1
$C(t)$ = composite C/A signal = ± 1

and the C/A signal structure is

$$C(t) = X_c(t) \oplus D(t)$$

where

$X_c(t)$ = periodic C/A signal ranging code with
code length = 1023 chips = 1 msec
code rate = 1.023×10^6 chips/sec
code period = 1×10^{-3} sec
$D(t)$ = navigation data at 50 bps
$\oplus$ = modulo-2 addition

The GPS baseband signal generation is organized and controlled to guarantee known timing relationships between the various components of the L_1 signal to ensure rapid signal acquisition and tracking and to provide signal synchronization in the receiver. For example, all carrier frequencies, codes, and data clocks are coherently derived from a single frequency standard. Thus, if the receiver is tracking the carrier, it can also derive a clock for the code generator.

2.5 NAVIGATION CONCEPT

The GPS navigational technique permits the user equipped with the proper receiver/processor to obtain his position and velocity with respect to an earth-centered reference. To avoid requiring users to be equipped with high-precision clocks, three-dimensional position and velocity information is obtained via four pseudo range and pseudo range rate measurements, respectively. PRN codes generated in the receiver are cross correlated with the PRN codes emitted by the satellites to determine position. The relative phase or equivalent time displacement τ between the receiver code and the incoming code is measured, allowing determination of the relative line of sight (LOS) range $R = c\tau$, where c is the velocity of light. Since user time is asynchronous with satellite time, the measurements made are not equivalent to the true geometric LOS range but are pseudo ranges (a pseudo range differs from the geometric range by a distance equivalent to the common receiver and satellite time bias). Referring to the user-satellite geometry shown in Fig. 2-3, the basic pseudo range measurement made from the n^{th} satellite can be expressed as

$$\left|\bar{R}_n\right|_{measured} = c\tau_n = \bar{r}_n \cdot (\bar{U} - \bar{S}_n) + c\Delta_u + c\Delta_n, \qquad (2\text{-}1)$$

where n = 1, 2, 3, 4 and where

$\bar{R}_n$ = true geometric LOS range from the n^{th} satellite to the user

$\bar{r}_n = \bar{R}_n / \left|\bar{R}_n\right|$ = unit vector from the n^{th} satellite toward the user

$\bar{U} = (x, y, z)$ = position vector that defines the location of the center of the user's antenna

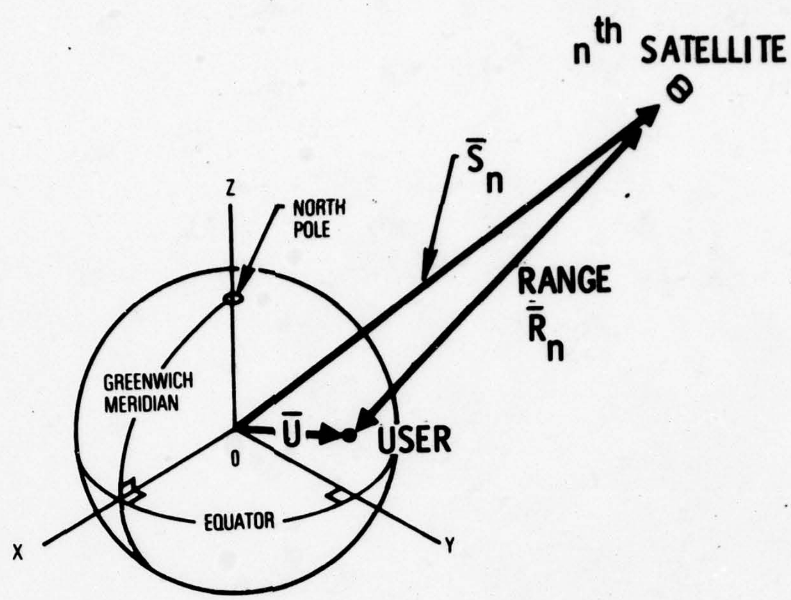


Fig. 2-3. User-Satellite Geometry

$\bar{S}_n = (u_n, v_n, w_n)$ = ephemeris vector that defines the location of the n^{th} satellite

Δ_u = user oscillator time bias uncertainty with respect to GPS system time

Δ_n = n^{th} satellite oscillator time bias uncertainty with respect to GPS system time

Simultaneously with the pseudo range measurements, the user equipment measures the range rate from each satellite by measuring the doppler shift on each transmitted satellite carrier. With the frequency of the user's oscillator asynchronous to the satellite's oscillator frequency, a pseudo range rate is measured rather than true LOS range rate. The pseudo range rate measurement from the n^{th} satellite is given by

$$\left|\dot{\bar{R}}_n\right|_{measured} = \bar{r}_n \cdot (\dot{\bar{U}} - \dot{\bar{S}}_n) + \lambda\Delta f_u + \lambda\Delta f_n \qquad (2-2)$$

where

$\dot{\bar{U}} = (\dot{x}, \dot{y}, \dot{z})$ = velocity vector that defines the time rate of change of position vector $\bar{U}$

$\dot{\bar{S}}_n = (\dot{u}_n, \dot{v}_n, \dot{w}_n)$ = velocity vector of the n^{th} satellite

Δf_u = user's oscillator frequency bias uncertainty with respect to the GPS system oscillator

Δf_n = n^{th} satellite oscillator frequency bias uncertainty with respect to the GPS system oscillator

$\lambda = cf$ = wavelength of satellite's transmitted carrier

Using tracking information obtained from monitor stations, the MCS provides the user, through satellite updates, the time and frequency biases of the satellite's oscillator relative to GPS system time and frequency. These biases (Δ_n and Δf_n) are applied as a compensation to the measured pseudo range and pseudo range rate measurements to form the so-called "corrected" pseudo range and pseudo range rate measurements

$$\rho_n \stackrel{\Delta}{=} \left|\bar{R}_n\right|_{meas} - c\Delta_n = \bar{r}_n \cdot (\bar{U} - \bar{S}_n) + c\Delta_u \tag{2-3}$$

$$\dot{\rho}_n \stackrel{\Delta}{=} \left|\dot{\bar{R}}_n\right|_{meas} - \lambda\Delta f_n = \bar{r}_n \cdot (\dot{\bar{U}} - \dot{\bar{S}}_n) + \lambda\Delta f_u \tag{2-4}$$

where n = 1, 2, 3, 4.

Given the nominal value of each satellite's ephemeris, the unit vector from the n^{th} satellite to the user is

$$\bar{r}_n = \frac{\bar{R}_n}{\left|\bar{R}_n\right|} = \frac{\bar{U} - \bar{S}_n}{\rho_n - c\Delta_u} \tag{2-5}$$

Equation (2-3) represents a system of four equations in terms of the set of four corrected pseudo range measurements (ρ_1, ρ_2, ρ_3, ρ_4) and the four unknowns (x, y, z, and $c\Delta_u$). Thus, solution of these equations yields the user's clock bias Δu and the user's position $\bar{U}$ = (x, y, z).

Using the computed position vector $\bar{U}$ and the known position and velocity vectors of the four satellites, Eq. (2-4) represents a system of four equations in terms of the four corrected pseudo range rate measurements ($\dot{\rho}_1$, $\dot{\rho}_2$, $\dot{\rho}_3$, $\dot{\rho}_4$) and the four unknowns ($\dot{x}$, $\dot{y}$, $\dot{z}$, and $\lambda\Delta f_u$). Thus, solution of these equations yields the user's velocity vector $\dot{\bar{U}} = (\dot{x}, \dot{y}, \dot{z})$ as well as the frequency bias of the user's oscillator. It may be noted from Eqs. (2-4) and (2-5) that solution of the user's velocity first requires solving for position since the unit vector $\bar{r}_n$ in Eq. (2-4) is a direction cosine weighting of the velocity vector ($\dot{\bar{U}} - \dot{\bar{S}}_n$) between the user and the n^{th} satellite.

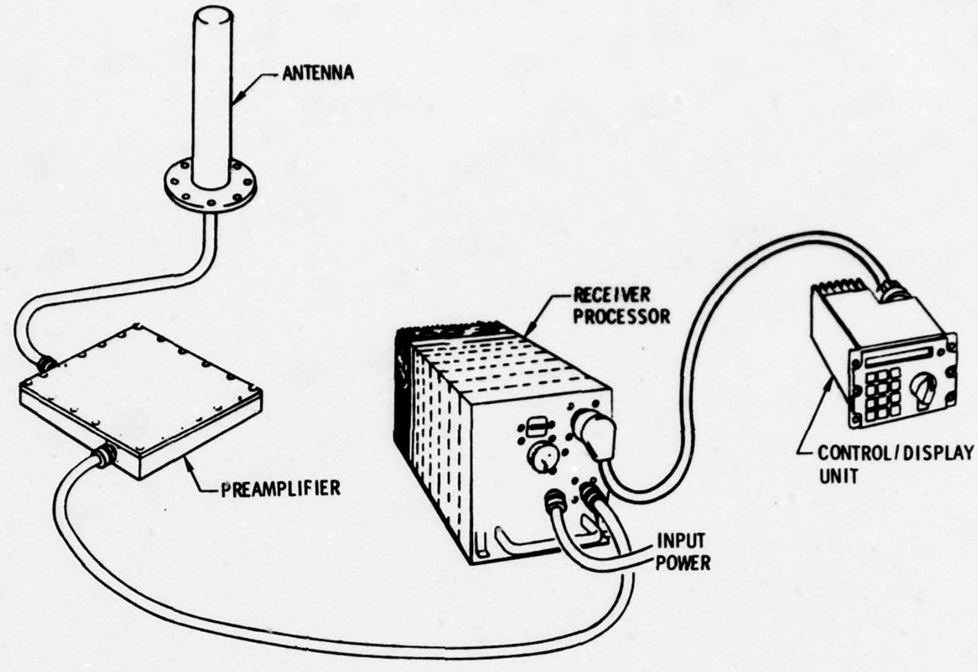
2.6 USER SEGMENT

The user navigation requirements dictate the GPS user equipment's sophistication. In general, the user equipment can be configured to operate as a stand-alone navigator or to perform as a receiver sensor when stripped of its display and navigation software. The stand-alone navigator consists of an antenna, receiver, data processor, control/display unit (CDU), and the attendant computer programs. The receiver selects the navigation signal from four satellites and measures pseudo range and pseudo range rate. The processor converts these measurements into usable navigation information. The navigation solution is obtained in earth-centered coordinates and is subsequently converted and displayed in geographic coordinates or any other coordinate system desired by the user. The

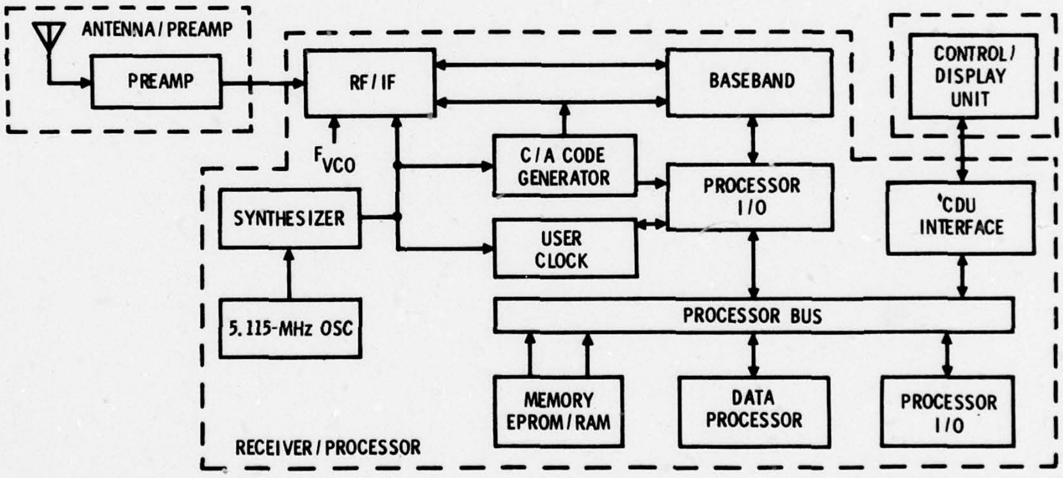
receiver sensor configuration provides pseudo range and pseudo range rate to any host navigator, or it can be combined with other navigation sensors into an integrated navigation system.

2.6.1 Z-set

The Z-set has been developed as a prototype for low-cost user equipment. The Z-set is configured as a stand-alone navigator. Figure 2-4 illustrates the Z-set hardware and shows its functional block diagram. The antenna provides hemispherical coverage at L_1, with the antenna gain and pattern directivity dictated by the user application. The separate preamplifier assembly provides installation flexibility and maintains the Z-set overall noise figure with close mounting to the antenna (less than four feet). The receiver/processor consists of a receiver with a multiple downconversion rf/IF unit, baseband loops and detectors, frequency synthesizer, C/A code generator, user clock, 5.115-MHz reference oscillator, and receiver input/output (I/O) connected to the processor bus. The processor is the LSI-11 16-bit microprogrammable minicomputer with 32,000 words/16 bits of storage, of which approximately 6,000 words are of randomly accessable memory (RAM) and 26,000 words of erasable/programmable read-only memory (EPROM). The processor I/O performs the data transfer operation with the receiver via the processor bus, and the CDU interface performs the same function for the CDU. The CDU consists of a microprocessor memory (3,000 words of PROM and 256 words of RAM) and a universal asynchronous receiver/transmitter terminal to interface with the receiver/processor. The CDU front panel provides a single-line, light-emitting diode (LED) display, a keyboard for data entry, and the switches to select the desired mode of operation and readout. The readout is a ten-character display of LEDs.



a) EQUIPMENT



b) BLOCK DIAGRAM

Fig. 2-4. Z-Set

The computer programs control the receiver processes, perform the navigation function, accept operator inputs, and provide outputs. They also enable the Z-set to sequentially acquire and track satellite signals based on data entries for initial conditions and filter estimates of current and predicted satellite and user positions. The navigation function filters all available measurement data to solve for user position and velocity and to determine the prediction data required for the receiver's next satellite acquisition cycle. In addition, the computer programs accept the operator-generated inputs and integrate them into the data base for the navigation filter and the receiver initialization.

2.6.1.1 Functional Description

The technical intricacies of the Z-set operation are mainly contained in the receiver rf/IF unit, the baseband loops and detectors, and the data processor and its stored program functions. The following functional description of the Z-set limits itself to these three broad areas. The other functions identified in the block diagram (Fig. 2-4) are self-explanatory and have little impact on a general Z-set description.

The receiver consists of a single rf/IF channel sequenced through the four satellites under control of the processor. The channel contains a preamplifier and bandpass filter arrangement that sets the receiver noise figure at around 5 dB. The amplified incoming L_1 navigation signal at 308F, where F = 5.115 MHz is downconverted four times, beginning with the first downconversion via the local oscillator to the first IF at 36F = 184.1 MHz. The locally generated C/A code is biphase modulated onto a local oscillator signal at 272F. This removes the C/A code and downconverts the

resultant data modulated signal to the second IF at 6.5F = 33.2 MHz. After further amplification controlled by the automatic gain control network, the third downconversion follows at 1.5F = 7.67 MHz. The fourth downconversion is at baseband, where additional bandpass filtering is accomplished.

The baseband consists of a Costas loop and lock indicator; a code loop error detector; and detectors for signal availability, automatic frequency control, and automatic gain control. The Costas loop, which demodulates the suppressed carrier signal, consists of in-phase (I) and quadrature (Q) multipliers and low pass filters. The quadrature output detector is filtered using an integrate and dump circuit to provide code alignment information. The I and Q filtered signals are fed to the baseband detectors as dc voltages. In addition, the baseband signal processing extracts phase offset information with the Costas loop multiplier and obtains frequency offset information with the automatic frequency control detector. Once the Costas loop locks in the carrier phase tracking mode, the system data is coherently extracted. The code error detector provides the measure of correlation between the received and local code and a means of matching the local code to the received code.

The LSI-11 data processor has been modified to include the floating point arithmetic chip and to interface with the receiver, the CDU, and an instrumentation device (HP-21MX). The 16-bit word consists of two 8-bit bytes. The LSI-11 standard instruction set has been extended for the double precision floating point and register save and restore operations. The processor has eight addressing modes and uses automatic priority for the interrupt structure. The computer program development specification (Ref. 1) provides a detailed summary of the instruction set, instruction execution times,

and addressing modes. The data processor 6,000-word RAM memory has 2,000 words of critical data memory built of C-MOS chips backed up by battery power to prevent the loss of critical variables during power failures. The remaining RAM memory segment uses static NMOS, which must be reinitialized at every power-up.

The Z-set programmed functions are implemented by computer programs through ten separate functions. A brief description of these software functions follows:

a. System Monitor. The system monitor controls the transition between the different Z-set states and the almanac update and supervises the Z-set modes of operation.

b. Receiver Processing. The receiver processing function selects the receiver hardware configuration desired, controls the voltage-controlled oscillator (VCO) device, and monitors the receiver as it performs signal acquisition and sequences through the satellites selected for use. This function computes system time, demodulates the satellite data message, and provides corrected measurements of pseudo range and pseudo range rate.

c. Control/Display Processing. CDU processing receives data blocks from the operator data entries and display requests and provides outputs of periodic navigation information and Z-set status.

d. Satellite Data Gathering. This function collects the satellite data message from the receiver processing for developing the ephemeris, almanac, and clock correction terms.

e. Navigation. The navigation function combines the measurement data in a Kalman filter to compute the Z-set position, velocity, time, and frequency errors. This processing incorporates pseudo range, pseudo range rate, and CDU-entered altitude. Additionally, this function estimates the slant range and doppler velocity for the receiver processing function to aid in the acquisition of the next satellite.

f. Satellite Selection. This function selects the optimum constellation of four satellites based on the best geometric dilution of precision (GDOP) index (Sec. 6.2) and as modified by the satellite health indicators and the anticipated visibility time to the user. The selected satellite constellation is periodically updated to maintain the optimum set of four.

g. Built-In Test. The built-in test provides the power start-up sequence for the Z-set computer programs and background self-test for program and critical data memory verification. This function collects the Z-set error history and makes it available at the CDU maintenance position and the instrumentation interface.

h. Instrumentation. This function informs an optional instrumentation data processor of the current availability of test and performance data. The transfer of data from the Z-set must be initiated by the instrumentation data processor on a noninterference basis.

i. Executive. The executive schedules the system tasks based on the time and priority of the multitasks of the Z-set computer programs.

j. Satellite Position Computation. This function gives the position of any satellite whose almanac or ephemeris data are available. This information is needed for navigation processing, satellite selection, and data gathering functions.

2.6.1.2 Modes of Operation

The major modes of operation of the Z-set are initialization, time to first fix (TTFF), sequential track, and almanac collect. These system modes provide a simplified overview of the Z-set system monitor states. Figure 2-5 illustrates these modes with the Z-set computer programs state flow diagram.

The initialization mode begins with the power-up sequence and ends with the start of the TTFF mode. The power-up sequence occurs whenever the power fails, a restart interrupt

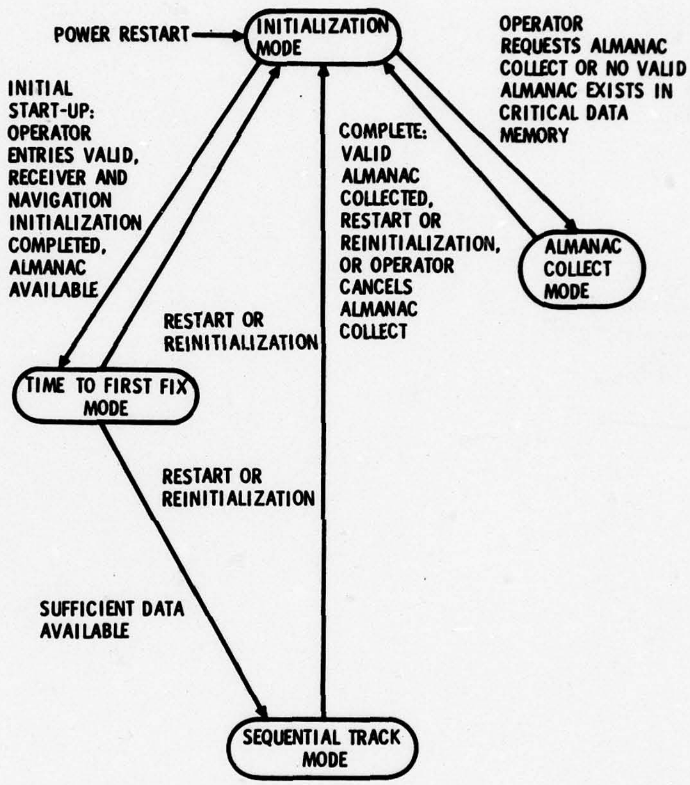


Fig. 2-5. State Diagram of Z-Set Operating Modes

appears, a software error is detected, or the operator requests it. This power-up sequence initiates system processing to verify the satellite almanac, clear the dynamic part of the critical data memory, and begin the receiver initialization process. With successful completion of the power-up sequence, the initialization mode enters the test background loop, and the system monitor begins its review of the collected information required to enter the TTFF mode. The background loop self-test occurs only when no other system function is active. When the receiver and navigation filter initialization processes are complete and a valid almanac exists in the critical data memory, the system monitor declares the initialization mode complete and enters the TTFF mode.

The TTFF mode performs satellite acquisition and the associated data gathering needed to enter the sequential track mode as quickly as possible. The satellite selection phase determines the initial set of satellites to be acquired and tracked. This is followed by the initial acquisition of the chosen satellite set, with the system monitor directing the receiver processing function to perform a variable time-dwell on each satellite. Once a satellite is acquired, a frame of data is acquired before the search for the other satellites begins. After the initial acquisition of the first satellite, the receiver processing function instructs the navigation function to perform a Kalman filtering cycle on the time-corrected measurements of pseudo range and pseudo range rate. The updated navigation state filter data provide a pseudo range estimate to the receiver processing function to speed acquisition of the next satellite. Once all four satellites have been acquired and the data has been retrieved, the synchronization is accomplished by sequentially cycling through the four satellites for a fixed time-dwell of 1.2 sec. For cyclic reacquisition, the satellites are reacquired using a variable

time-dwell without data demodulation. With the four satellites operating on fixed time-dwell, the system monitor enters the sequential track mode.

The sequential track mode is the normal status of the Z-set. In this mode the CDU processing function provides CDU outputs, the self-test loop monitors system health, and the system monitor periodically invokes the satellite selection function to update the satellite constellation. As the sequential track mode is entered, the receiver processing function data editing procedure provides time-corrected pseudo range and pseudo range rate measurements accompanied by a "goodness" estimate for each measurement. This process begins the navigation function. The eight-state Kalman filter then updates the estimate of the user's position, velocity, time, and frequency errors. The fixed time-dwell of 1.2 sec continues during sequential track unless a satellite must be replaced, new telemetry data must be gathered, or the receiver VCO needs recalibration. In these cases the system monitor directs the proper function to provide the needed process.

Satellite acquisition depends on the almanac data stored in the critical data memory. Almanac data are transmitted by each satellite. If no valid almanac exists in the Z-set, acquisition of the satellites may be performed in the search-the-sky mode. This mode attempts to acquire a satellite selected from an arbitrary sequence with the widest possible search windows. If the satellite cannot be acquired or if complete almanac data cannot be collected, almanac collection from the next arbitrary sequence is attempted.

3. Z-SET SHIPBOARD CONFIGURATION

Engineering analyses, evaluations, and surveys were conducted to identify the Z-set modifications needed to achieve full performance in a shipboard environment. Since the Z-set was designed for airborne applications, it is not surprising to find that the antenna, preamplifier, display, and power supply require some modification or adjustment for maritime use. Though many of the Z-set hardware modifications are dictated by the marine use, many changes result from the scope of the planned demonstration, the lack of a specific ship selection at this time, and the desire by MARAD and the GPS JPO to show the operational potential of the Z-set.

3.1 ANTENNA

The Z-set antenna requirements are simply stated. The antenna gain must be sufficient to deliver a signal to the preamplifier input that is strong enough for the receiver to process properly. It must do this for all combinations of azimuth, elevation, and ship roll angles within the ranges specified for normal operation:

Ship-to-satellite elevation angles	10 to 90 deg
Ship-to-satellite azimuth angles	0 to 360 deg
Ship roll angles	±25 deg (max)

The worst-case antenna coverage occurs when the roll axis is perpendicular to the LOS between the ship and the satellite. Since the antenna will be mounted so that the axis of symmetry of its radiation pattern is perpendicular to the deck plane, the required coverage with respect to a vertically oriented axis of symmetry translates to an elevation angle coverage of from -15 to +90 deg.

3.1.1 Required Carrier-to-Noise Density Ratio

The signal delivered by the antenna must be sufficient to provide the required minimum carrier-to-noise density ratio C/N_o. The C/N_o requirement may be inferred from the Z-set specification (Ref. 2). Alternatively, the required C/N_o may be determined by analysis of the receiving system design parameters: The performance based on analysis of the receiving system should exceed the specified C/N_o requirement.

Table VI of Ref. 2 specifies a maximum noise figure of 5 dB at the preamplifier input and a maximum cable loss of 0.4 dB from antenna output to preamplifier input. The preamplifier noise temperature referred to the antenna connector is therefore

$$T_r = (L-1)\ T_o + L\ (F-1)\ T_o = 715\ K$$

where

$$F = 5\ dB = 3.16$$
$$L = 0.4\ dB = 1.096$$
$$T_o = 290\ K$$

The receiving system temperature also includes the antenna temperature. This has been estimated at 150 K, including the effects of sky temperature and the illumination of the sea surface by the lower regions of the antenna coverage pattern. This estimate is conservative; note that even a completely isotropic antenna mounted above the earth's surface at 290 K would measure nearly 150 K because of the cold sky. The sea surface is much "colder" than 290 K because of its high reflection coefficient. In any event, the contribution of the antenna temperature to the receiving system noise temperature is masked by the much larger noise temperature of the preampli-

fier. Accordingly, the system noise temperature referred to the antenna connector is estimated as $T_s = T_r + T_a = 715 + 150 = 865$ K. The noise density is $N_o = kT_s$, where k is Boltzman's constant. This results in $N_o = -199.2$ dBW/Hz. The minimum signal at the antenna is given in Table VI of Ref. 2 as C = -163 dBW. Hence, the minimum C/N_o requirement determined in this way is $C/N_o = -163 + 199.2 = 36.2$ dB-Hz.

The Z-set specification (Ref. 2) states a 25 dB jamming margin requirement. While the relevance of this requirement to the demonstration may be discounted, one can nevertheless calculate an implied C/N_o requirement on the assumption that a noise jammer would be used. The maximum jamming plus signal level is stated to be -125 dBW (Table VIII, Ref. 2). Since this greatly exceeds the minimum signal level of -163 dBW, the -125 dBW level is essentially all jammer power. Assuming band-limited white noise jamming in a 6-MHz bandwidth, which is the bandwidth occupied by most of the signal energy, the jammer noise power density would be $N_{oj} = -125 - 67.8 = -192.8$ dBW/Hz. Combining this with the thermal noise density at -199.2 dBW/Hz gives $N_{ot} = N_o + N_{oj} = -191.9$ dBW/Hz. Therefore, the implied C/N_o requirement in the presence of maximum specified jamming is $-163 + 191.9 = 28.9$ dB-Hz.

The Z-set uses a Costas loop with a 20-Hz bandwidth. One can estimate its C/N_o requirement as:

Threshold margin		10 dB
Costas loop loss		6 dB
Tracking bandwidth		13 dB
	C/N_o =	29 dB-Hz

Data presented by Magnavox at the Critical Design Review (13 December 1977) indicates that carrier lock was actually achieved at C/N_o = 26 dB-Hz.

To summarize, the C/N_o requirement has been estimated in several different ways:

o	Requirement based on thermal noise	36.2 dB-Hz
o	Requirement, thermal noise plus noise jamming	28.9 dB-Hz
o	Estimate based on nominal receiver parameters	29.0 dB-Hz
o	Performance reported at Critical Design Review	26.0 dB-Hz

To derive the antenna gain requirements, the C/N_o requirement was taken as 29 dB-Hz.

3.1.2 Gain and Patterns

To achieve C/N_o = 29 dB-Hz in the presence of the estimated level of thermal noise requires a signal at the antenna connector of C = -199.2 + 29 = -170.2 dBW. In the presence of maximum specified jamming, the required carrier power becomes C = -191.9 + 29 = -162.9 dBW, which agrees with the minimum stated signal level of -163 dBW (Ref. 2).

In determining the antenna requirement for the demonstration, providing the breadth of angular coverage under all conditions (i.e., ship roll angles of ± 25 deg maximum, all elevation angles above 10 deg) was a paramount consideration. The jammer threat was largely discounted for commercial vessels in a normal environment. Obviously, one would prefer an antenna with the 7-dB greater directional gain implied by the

jammer threat if the greater gain could be achieved without sacrifice of the required coverage. An examination of five candidate antennas showed that while most of them met the higher gain requirements over the restricted coverage angles needed for a level deck, their pattern coverage at low (actually negative) elevation angles fell off sharply, restricting performance to small roll angles.

The user-satellite link budget for a zero-dBIC receiving antenna at satellite nadir is given in Table 3-1.

Table 3-1. User-Satellite Link Budget

Available satellite power	+13.5 dBW
Satellite antenna nadir gain	+11.8 dBIC
Specified atmospheric loss	-2.0 dB
Space loss at nadir	-182.5 dB
Available power with 0-dBIC receiving antenna	-159.2 dBW

Note that the atmospheric loss can be considered small for the purpose of this demonstration (for instance, at the L_1 frequency rainfall produces negligible attenuation). Therefore, to arrive at a better understanding of what is likely to happen under normal conditions, the nominal received power at nadir was taken as -157.2 dBW for a 0-dBIC antenna. Margins will be added as the final step in the specification process.

Since the signal delivered by the antenna must be at least -170.2 dBW, the antenna gain at nadir (elevation angle = 90 deg) must be at least -170.2 + 157.2 = -13.0 dB. This figure must be adjusted for other user-satellite elevation

angles by taking into account the variation in satellite antenna gain and the variable range loss. On this basis, an antenna gain versus elevation angle requirement was constructed corresponding to the C/N_0 = 29 dB-Hz curve of Fig. 3-1. Also shown are the gain curves of the four Texas Instrument volute antennas and the antenna proposed for Z-set use by Magnavox.

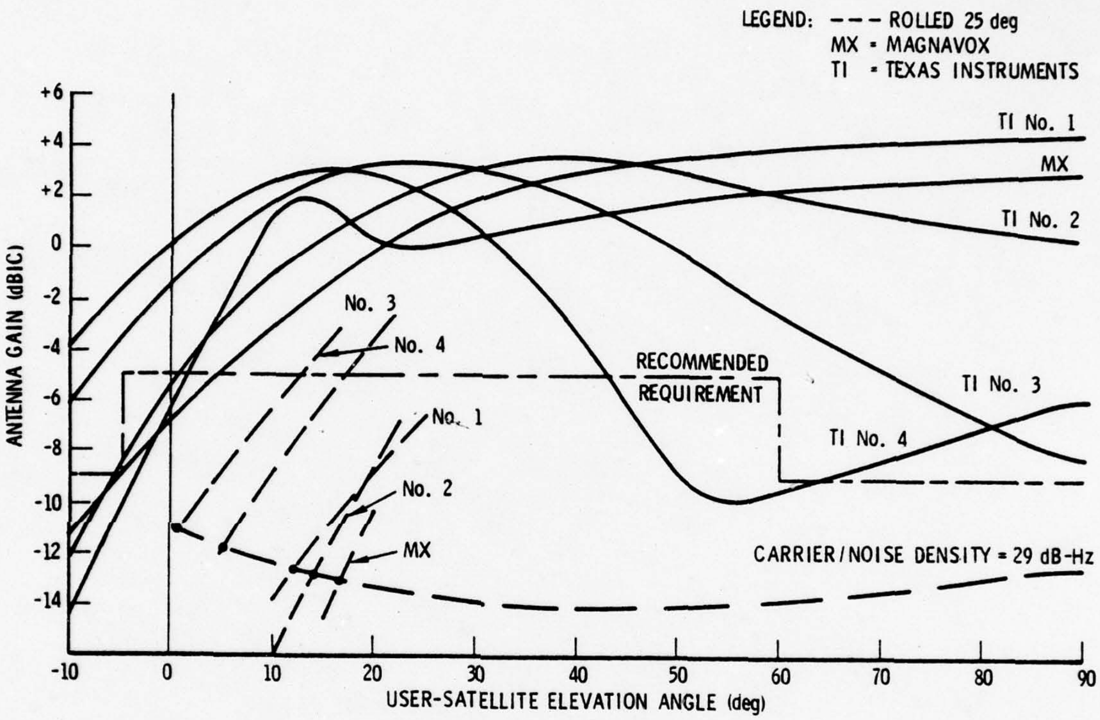


Fig. 3-1. Antenna Selection

The solid curves depict the antenna gain as a function of elevation angle for a vertical orientation (i.e., no ship roll). Portions of these curves have been displaced by 25 deg in elevation angle and redrawn in dashed form; these represent the

worst-case roll conditions. The intersections of these dashed curve antenna patterns with the C/N_o = 29 dB-Hz requirement curve define the minimum user-satellite elevation angle that can be accommodated in the presence of the worst-case roll. It may be seen that volutes 3 and 4 are capable of operation at elevation angles of less than 10 deg, while the other antennas cannot meet this requirement. The antenna described by Magnavox was most deficient in the presence of roll. While the minimum margin of volutes 3 and 4 was approximately the same for a 25-deg roll, volute 3 gives greater margin under most conditions of operation and is therefore preferred.

The conclusion to be drawn (Fig. 3-1) is that any antenna will do if its gain is greater than -12 dBIC for angles up to 105 deg from its vertical axis of symmetry and at all azimuth angles. When it is recognized that an antenna radiating uniformly into the required coverage region would have a gain of -1.0 dBIC even if it were only 50 percent efficient, it becomes apparent that almost any antenna designed for broad coverage should be adequate. Undoubtedly, the fact that three out of the five candidate antennas fail this test is a result of their being designed for another application that requires higher gain (for better jamming resistance) in a reduced angular coverage region.

Thus, the recommended antenna gain specification proposed is: With the antenna oriented such that its axis of symmetry is vertical, its gain at any azimuth angle and for all elevation angles from -5 to +60 deg shall be at least -5 dBIC; at elevation angles from -15 to -5 and from +60 to +90 deg, the gain shall be at least -9 dBIC. Of the five candidate antennas, only volute No. 3 meets this specification; however, for the reasons stated, it is felt that a superior antenna can easily be provided once the requirement is identified to

potential vendors. Preference should be given to an antenna that surpasses the recommended gain specification by an ample margin. Note (Table 3-2) that an antenna that provides the gain required by the recommended specification would have a margin of 3.4 dB under the worst-case condition.

Table 3-2. Performance of Candidate Antennas for Demonstration

Antenna	Minimum Gain Margin, dB		Elevation Angle for Minimum Gain Margin, deg		Minimum Usable Elevation Angle with 25-deg Roll
	Without Roll	With 25-deg Roll	Without Roll	With 25-deg Roll	
TI No. 1	9.2	-1.5	10	10	12.5
TI No. 2	11.5	-3.5	10	10	14.0
TI No. 3	4.5	3.5	90	10	5.0
TI No. 4	4.2	3.0	55	80	1.0
Magnavox	13.5	-6.5	23	10	17.0
Recommended specification	3.6	3.4	90	10	0

3.2 CABLE SELECTION

An assortment of preamplifiers with gains ranging up to 50 dB, and perhaps more, in the frequency band of interest is commercially available. Prices in small quantities are under $1,000. On the other hand, the choice of cable is more restricted. One wishes to select a cable type that meets the shipboard environment, is low in cost and easily installed, and whose attenuation can be adequately compensated by the preamplifier. Given a set of reasonable cable parameters, a suitable preamplifier can usually be found. For these reasons, the cable choices will be considered first. The principal considerations that determine cable selection for this application are:

a. Choice of dielectric material. Polyethylene and Teflon are the chief contenders for this application. The latter offers a broader temperature range, but it is more expensive and in some ways more difficult to work with. The temperature range for polyethylene (-40 to +80 C) is adequate for this application; therefore, the use of a polyethylene cable is recommended.

b. Use of single versus double braid shielding. Double braid shielding gives superior protection against external interference. As mentioned previously, high level interference is a potential problem in this application; nevertheless, the use of double braid shielding does not appear warranted. Should such strong interference be present, it would probably be picked up much more readily in the antenna itself since the total length of the cable will not normally exceed 200 ft. Strong interference fields will usually extend over larger distances. An exception would be a case where the cable is run past a source of high-power radiation such as a radar transmitter beam. In such a case, intelligent design of the installation layout will be more effective in preventing interference than the use of double shielded cable.

c. Use of armored versus unarmored cable. This choice should be based on the degree of exposure and protection given the cable run. If the cable is placed in permanent cable ducts, additional protection will not be necessary. On the other hand, a temporary installation for an experimental or demonstration program might offer less than perfect protection. It appears, therefore, that the use of an armored cable is warranted.

d. Attenuation per unit length of cable. It is tempting to specify a very low-attenuation cable. However, at this frequency (1.575 GHz), cables with minimal attenuation have large diameters (one inch or more). Such cables are difficult to handle and more difficult to install because of minimum bending radius requirements. They are also expensive. Since the preamplifier gain can compensate for any reasonable amount of cable loss, the attenuation of the cable is of secondary importance.

Table 3-3 lists the chief contenders for this cable application and the corresponding evaluations. It will not be obvious that the evaluations are appropriate until the available preamplifiers are also considered and the combined characteristics of the preamplifier, cable, and receiver are determined. Table 3-3 includes only single shielded armored cable using polyethylene dielectric with a 50-ohm characteristic impedance.

Table 3-3. Coaxial Cable Selection for Demonstration

RG Type No.	Maximum Diameter, in.	Attenuation, dB/100 ft	Evaluation
221/U	1.195	4.7	Excessive size
219/U	0.945	6.0	Excessive size
224/U	0.615	8.0	Excessive size
215/U	0.475	12.0	Use with recommended preamplifier[a]

[a]May require additional postamplifier for cable lengths greater than 160 ft.

Since cable runs will normally not be longer than 200 ft, the use of RG215/U will generally be acceptable. With a 200-ft length, the attenuation of RG-215/U will be 24 dB. It will be shown that the selected preamplifier combination will provide satisfactory low-noise performance with this amount of attenuation. For a very short cable run, excess gain will be available. The dynamic range of the receiver may not be sufficient to accommodate the excess gain, considering the power level variations of the signal of interest and the interference environment. To secure improved protection against overload and interference, it would be desirable to insert an in-line

attenuator in the cable path when operating with very short cables.

3.3 PREAMPLIFIER

Remarkable progress in the art of low noise, solid-state microwave amplifiers has been accomplished in the last few years. For narrowband applications at the frequency of interest, noise figures of 2.5 dB are now specified in commercial units of reasonable price. No attempt was made to survey all the manufacturers that could supply a suitable preamplifier for this application. A well-known production source (Avantek, of Santa Clara, California) was contacted. This supplier offers three catalog items of potential interest. It is believed that other manufacturers can offer similar products at competitive prices. The characteristics and approximate prices of these Avantek amplifiers are summarized in Table 3-4.

Table 3-4. Representative Preamplifier Characteristics

Avantek Model No.	Frequency Band for 0.25-dB Gain Flatness, MHz	Min Gain, dB	Max Noise Figure, dB	Min Power Output for 1-dB Gain Compression, dBm	Approximate Price, $
AM-1660[a]	1535-1660	50	2.5	+12	895
AM-1661	1535-1660	50	2.5	+12	800
AM-1662	1535-1660	30	2.5	+10	650

[a]This unit contains an integral narrowband filter which can be furnished tuned to 1.575 GHz. It was sold to Magnavox for the MARISAT program, and tuned to 1.539 GHz. This unit is of special interest in view of its capability to reject strong out-of-band interference.

The expression for the overall noise figure of the receiving system, referred to the antenna feed terminals, is

$$F_o = F_1 + \frac{L - 1}{G_1} + \frac{L(F_2 - 1)}{G_1} \qquad (3\text{-}1)$$

where F_o = system noise figure referred to the antenna terminals

F_1 = noise figure of the preamplifier

G_1 = gain of the preamplifier

L = loss ratio (input/output) of the cable

F_2 = noise figure of the receiver (rF/IF module)

Note that as the gain of the preamplifier increases, the overall noise figure approaches that of the preamplifier.

Equation (3-1) was applied in deriving the values shown in Table 3-5. The values of L used correspond to the loss factor of 12 dB per hundred feet for RG-215/U cable. The receiver noise figure is taken as a worst-case value of F_2 = 9 dB (in accordance with Table XVIII, Ref. 2), and the preamplifier noise figure is assumed to be F_1 = 2.5 dB.

It is apparent that, with short cables, a preamplifier gain of 30 dB suffices to prevent degradation of the overall noise figure. For a 200-ft cable run, a 50-dB gain is required to obtain the full benefit of the preamplifier noise figure. Evidently, a 50-dB gain preamplifier will satisfy the requirements for all cable runs up to 200 ft, provided that the excess gain does not result in receiver overload with short cable runs.

For the types of receiving antennas under consideration, the signal input to the preamplifier may be expected to vary from a minimum of about -167 dBW to a maximum of about

-149 dBW for various user-satellite elevation angles above 10 deg and for roll angles up to 25 deg. (The maximum estimated

Table 3-5. Preamplifier Gain Versus Overall Noise Figure For Minimum and Maximum Cable Lengths

Cable Length (RG-215/U), ft	Preamplifier Gain, dB	Overall Noise Figure, dB
10	10	4.4
10	20	2.7
10	30	2.5
10	40	2.5
10	50	2.5
200	10	23.0
200	20	13.4
200	30	5.8
200	40	3.0
200	50	2.5

level assumes clear sky and a satellite effective isotropic radiated power (EIRP) 3.0 dB higher than the worst-case budgeted values.) Assuming a preamplifier with 50-dB gain and a very short connecting cable to the rF/IF module, the input level range to the rF/IF module will range from -117 to -99 dBW; this is well within the specified dynamic range (Table XVIII, Ref. 2) of -140 to -95 dBW. If a 200-ft length of RG-215/U cable (24-dB attenuation) is interposed, the input level to the rF/IF module will range from -141 to -123 dBW, 1 dB short of the specified minimum requirement. If a 53-dB preamplifier is specified, the results are as shown in Table 3-6.

Table 3-6. Range of Expected Input Levels at the rF/IF Module with a 53-dB-Gain Preamplifier

Cable Length (RG-215/U), ft	Minimum Expected Receiver Input, dBW	Maximum Expected Receiver Input, dBW
0	-114	-96
200	-138	-120

Table 3-6 shows that the minimum expected receiver input is 2 dB greater than the minimum required by the receiver, while the maximum expected receiver input is 1 dB less than the maximum tolerated by the receiver While this result is marginally acceptable, a more comfortable margin would be preferred, particularly in the presence of a high-interference environment. There are at least two ways to accommodate the 24-dB level differential associated with the use of cable runs that can vary as much as 200 ft between different installations:

a. Use a cable with less attenuation per unit length. For example, RG-219/U has an attenuation of 6 dB per hundred feet and the range of attenuations due to differing cable lengths would therefore be only 12 dB with its use. Unfortunately, RG-219/U is twice as thick as RG-215/U and is difficult to install. There are simpler ways to handle the problem.

b. Supply preamplifiers with at least two gain options. For example, an off-the-shelf 50-dB preamplifier could be the basic unit used for any installation. For maximum-cable-length installations (200 ft), this unit would be used in conjunction with an auxiliary 5-dB postamplifier to make up the additional cable loss.

The second option is clearly preferable and is therefore recommended. In high-interference environments, it may be desirable to insert a supplementary attenuator in the cable

path if the installation requires a very short cable. This reduces the chances for receiver overload.

The above recommendations assume that the estimated signal level input to the preamplifier is based on the use of an antenna that meets the minimum recommended gain requirement. It was shown that an antenna with up to 7 dB greater gain offered certain advantages and could probably be supplied without undue difficulty. Any increased antenna gain should be offset by reduced net preamplifier gain, which can be obtained by inserting compensating attenuation in the cable path at the input to the rF/IF module.

3.4 POWER CONSIDERATIONS.

A special ac/dc converter has been included in the shipboard Z-set configuration to allow operation from the 115-V ac, 60-Hz power source used onboard most commercial vessels. The standard Z-set operates at 115 V ac and 400 Hz. The demonstration preparations must also consider the power interruption characteristics of the selected ship plus the power requirements of the preamplifier and display. The Z-set has been designed for input power interruptions of up to 3 msec without any degradation in performance, and it can resume normal operation in less than 95 sec after power interruptions of up to 7 sec. For interruptions greater than 7 sec, the Z-set may require reinitialization. A separate power supply will be needed if the ship installation dictates a replacement for the current Z-set preamplifier and if the selected preamplifier cannot operate off the 12-V, 40-mA Z-set power supply. All the display candidates identified in Table 3-7 operate from a 115-V ac, 60-Hz power source and are thus compatible with the ship primary power source.

Table 3-7. Candidate Displays for Demonstration

	Intelligent with Computational Features		Nonintelligent		Intelligent without Computational Features
Model number	Beehive B-500	Delta Data 4500	Burroughs ID730	Ann Arbor K1632	HP2645-A, Option 12360B Card
HP21MX interface	12966A $950	12966A $950	12531D-001 $405	12531D-001 $405	12966A-001 $950
LSI-11 interface	DLV-11 $250 Cable BC053-X $50 + 50¢/ft	DLV-11 $250 Cable BC05C-X $50 + 50¢/ft			
Lines × characters displayed	25 × 80	25 × 80	12 × 40	16 × 32	24 × 80
Screen size, in.	12 (diagonal)		8.4 × 4.7	14 (diagonal)	5 × 10
Cabinet size (w × h × d), in.	20 × 16 × 27	19 × 16 × 27	15 × 10 × 7	20 × 15 × 23	17 × 13 × 26
Keyboard options	Standard upper/lower case, function and numeric keypads, 8 program function keys.	Standard upper/lower case, function and numeric keypads, 8 program function keys.	5 choices including typewriter keyboard, 10-key auxiliary.	Model KB 200B adds cursor, numeric and function keypads.	Standard, cursor numeric and function keyboard, 8 user defined software keys.
Operating temperature, °C	5 - 40	10 - 40	10 - 40	10 - 40	5 - 40
Relative humidity, percent	Up to 95	20 - 80	20 - 80	20 - 80	20 - 80
Remarks	Intel hex language	Assembly language	Gas discharge display filters		
Display cost	$2800 - $5880	$3700 - $4500	$3500	$1495	$3500

3.5 SHIPBOARD DISPLAY

This section addresses the requirements, selection, and data entries for the shipboard display. It also presents a potential scheme for the CDU data presentation adapted to the maritime user requirements and suitable for the demonstration.

3.5.1 General Requirements

The display requirements of the commercial maritime user differ markedly from the Z-set control/display features of the avionic user. To this end, a set of shipboard display requirements, partly based on the TRANSIT display and on discussions with shipboard personnel, was postulated to present the navigation data in a format suitable for operational use during the demonstration.

The display and keyboard should be within a single envelope, although a separate keyboard that forms an integral unit with the display is acceptable. The video screen area should be at least 40 to 50 square inches, and its format should consist of a mininum of 12 lines and 32 characters. The keyboard should include ten digits, decimal point, ± , and clear functions. Prompt, cursor, and programmable function keys are desirable. The display should permit interaction with the operator, such as calling up display modes and entering initial conditions. The display should be small, with a printer or recorder port, and should operate off a standard 115-V ac, 60-Hz power source.

3.5.2 Candidate Displays

The survey identified many candidate displays that met all the stated requirements for the demonstration. In addition

to the stated requirements, the survey considered intelligent displays with and without computational capability and nonintelligent displays (an intelligent display is one that can be programmed internally to present the information in the desired formats). Generally, the programmed routines need to be stored in nonvolatile memory within the display or in an ancillary unit that could load the display's volatile memory each time the unit is initiated. For the demonstration, the display can be either an intelligent or nonintelligent terminal since all computations and formatting are accomplished within the data switch. For operational use, the display must emulate the Z-set CDU; therefore, the operational unit must be programmable with some computational capabilities.

The results of the survey highlight the display candidates most desirable for the demonstration from the standpoints of flexibility and ease of use (Table 3-7). The Beehive B-500 and the Delta Data 4500 are the two candidates that best meet all postulated requirements. The B-500 must have the computational routines programmed on a separate computer in INTEL-HEX and then stored in PROMs in the B-500 for execution. The Delta 4500 has a resident assembler and can be programmed on-site. For either display, the program can be loaded through disc or tape peripherals. The B-500 has 16 programmable function keys in addition to the standard keyboard. In the nonintelligent display group, the Burroughs ID 730 appears more attractive because of the larger selection of optional keyboards for a more convenient operator interface and its smaller volume. None of the displays investigated met the environmental requirements of the Z-set. However, it is felt that the operating ranges of temperature and relative humidity for these displays are adequate to allow proper operation in the ship bridge environment.

3.5.3 Display Format

The shipboard display format presented here is one of many possible schemes. It was assumed that the display is controlled by an HP 21MX computer device and (with the display combined with the driver program) that it precisely emulates the Z-set CDU. This computer provides the additional functions needed to perform the demonstration and reduces the amount of software needed. The ground rules for the demonstration dictate that no Z-set software changes will be allowed (Sec. 4.1). The demonstration equipment will provide automatic initialization and will include estimated time of arrival to any waypoint, set and drift, and the ship's relative speed and heading.

The format for the shipboard display has been designed for a 24-line, 80-column display. The displayed information has been grouped into three sets. Columns 1 through 21 (the first set) contain a menu of the possible operator inputs. The next set, columns 22 to 52, contains the Z-set navigation variables and values. The modes of operation and diagnostic information are indicated in the third set. In developing this display, the natural flow of the Z-set functions (startup, reinitialization, etc.), all the switch positions and all valid combinations, and adherence to the basic rules for displaying information were considered. These rules include:

a. Operator inputs are preceded by a prompt, which occurs at the left-hand portion of the bottom line.

b. Each display item always appears at the same location on the screen regardless of the Z-set mode of operation.

c. If the operator makes an error during the keying in of input data, he may clear the input buffer and reenter the data. The inputs are displayed to the operator.

Figure 3-2a shows a presentation with all the possible items listed, and Fig. 3-2b shows a display operating in the navigation mode with the display menu suppressed.

```
00 MENU DSPLA

01 STARTUP            DAY-TIME         D  HH MM SS
02 REINITIALIZE       LATITUDE         N  DD MM                INITIALIZE
03 CALIBRATE          LONGITUDE        E DDD MM SS              CALIBRATE
04 MAG-TRUE NORTH     ALTITUDE         +  FFFFF    FEET         TRUE NORTH
05 WAY POINT NUM      EST POS ERROR      NNN.NN    NMI
06 ALMANAC COLL                                                 NORMAL  COLLECT
07 ALMANAC W-N        ACT SPEED            NN.N    NAUT         WIDE   UNCERTAIN
08 MAINTENANCE        ACT HEADING         DDD.D    DEG          3300000
                      DRIFT                NN.N    NAUT
                      SET                 DDD.D    DEG          STANDBY
10 LATITUDE           REL SPEED            NN.N    NAUT         NAVIGATE
11 LONGITUDE          REL HEADING         DDD.D    DEG          DEAD RECKON HH MM SS
12 ALTITUDE
13 ACT SPEED          WAY POINT NUM           0
14 ACT HEADING        LATITUDE         N  DD MM SS
15 DAY-TIME           LONGITUDE        E DDD MM SS
                      MAG VARIATION    +   DD.D    DEG
20 WP LATITUDE        DISTANCE           NNNN.N    NMI
21 WP LONGITUDE       BEARING             DDD.D    DEG
22 MAG VARIATION      ETA              DD HH MM

INPUT =
```

(a) MENU

```
00 MENU DSPLA

                      DAY-TIME         3  18 28 57
                      LATITUDE         S  10 21 42
                      LONGITUDE        W 152 54  6
                      ALTITUDE         +      97   FEET         TRUE NORTH
                      EST POS ERROR          .02   NMI

                      ACT SPEED              8.2   NAUT
                      ACT HEADING          341.8   DEG
                      DRIFT                  1.2   NAUT
                      SET                  190.2   DEG
                      REL SPEED              9.3   NAUT         NAVIGATE
                      REL HEADING          345.4   DEG

                      WAY POINT NUM            0

INPUT =
```

(b) NAVIGATION MODE

Fig. 3-2. Display Presentation

4. AT-SEA DEMONSTRATION

The objectives of the Z-set at-sea demonstration are to:

- Provide performance data to evaluate the economics of GPS satellite navigation relative to commercial shipping
- Show the Z-set's inherent potential for automatic ship operation

These objectives will be accomplished by comparing the GPS position and velocity readings with estimates of these quantities obtained from other navigation systems. From these data, the improvement in knowledge of the ship's position and the maintenance of a desired track can be calculated to avoid bad weather, minimize fuel expenditure, and accommodate destination changes. Data will be collected to indicate the feasibility of using GPS in an automatic steering mode.

The projection to quantify economic improvement requires that specific, realistic ship scenarios be postulated and that the economic advantages of GPS navigation be computed using appropriate models. This projection is considered beyond the scope of this program. The demonstration has been structured to minimize requirements on ship personnel.

4.1 BASELINE CONFIGURATION

To specify the data and data processing requirements of the at-sea demonstration, it is necessary to assume a baseline system that describes the equipment configuration and its processing capabilities and the desired degree of automation in the operation of the shipboard equipment. The ground rules given herein are subject to modification as the project proceeds into

Phase II and pragmatic considerations become evident; for example, the too-high cost of achieving the degree of automation sought or the nonavailability of the specified equipment on a timely basis.

Figure 4-1 is a functional block diagram of the baseline configuration for the demonstration. The Telex Data Switch (TDS) is the onboard computer that directs all demonstration activities and communicates with the shore via the MARISAT terminal. The navigational aids and ship's attitude reference are connected with the computer through standard Hewlett-Packard (HP) interface cards and provide the desired data under control of the TDS executive. Other data such as sea state, weather conditions, and celestial fixes can be manually entered into the TDS via the teleprinter. The following equipment descriptions assume that any modifications needed for the equipment to operate as specified will be made as part of the Phase II tasks.

a. <u>Telex Data Switch (TDS)</u>. The TDS, hereafter referred to as data switch, HP 21MX, or simply computer, is an HP 2108B computer adapted by Magnavox to perform shipboard monitoring functions and to transmit or receive data via the MARISAT terminal. The data switch will store the computer programs necessary to perform the processing functions of the demonstration and will provide the dedicated storage for the Z-set demonstration. The data switch will include the necessary HP interface cards to interconnect with the equipment shown in Fig. 4-1.

b. <u>Z-Set.</u> The Z-set will be the shipboard configuration defined in the prime item development specification (Ref. 2) and the computer program development specification (Ref. 1). The Z-set hardware and software changes necessary for the demonstration are discussed in Sec. 3. No changes to the software programs resident in the Z-set memory will be made. The Z-set will allow direct memory access via the I/O port, and the CDU port will be connected to the data switch through an HP 12531D terminal interface card.

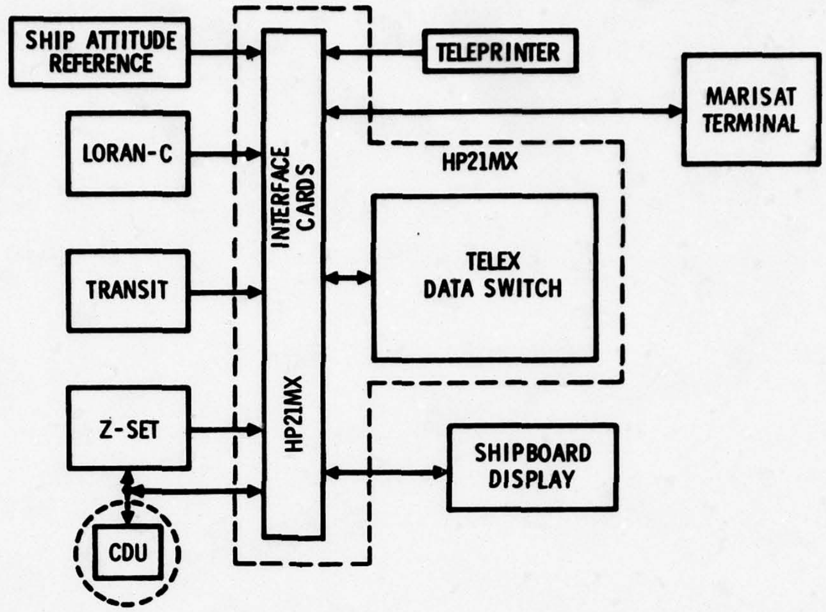


Fig. 4-1. Baseline Configuration for Demonstration

c. TRANSIT. The TRANSIT terminal will be an MX 1102-NV satellite navigator. Heading information from the ship's gyrocompass and velocity data from the ship's speed log will be connected to this terminal and will be available to the data switch. The data switch will collect data on an interrupt basis with the HP 12531D terminal interface card.

d. LORAN-C. The LORAN-C receiver will be the Teledyne TDL 708 marine model. The receiver-processor configuration will allow direct interconnect to the data switch with four HP 12554A interface cards.

e. MARISAT Terminal. The MARISAT terminal will be the Magnavox MX 111 terminal or the COMSAT general terminal. It is assumed that the data switch works equally well with either type and that no special hardware provisions are required.

f. <u>Ship Attitude Reference.</u> The attitude reference package will be the Jet Electronics and Technology, Inc., displacement gyro model VG-204F, which will output pitch and roll angles. The yaw angle will be obtained from the ship's gyrocompass via the TRANSIT terminal. The connection to the data switch will be via the HP 91000A analog-to-digital converter interface card.

g. <u>Shipboard Display.</u> The shipboard display will be the Beehive B-500 or the Delta Data 4500. This display will be connected to the data switch via the HP 12966A, an asynchronous communications interface card.

4.2 DEMONSTRATION PHILOSOPHY

The approach for accomplishing the demonstration objectives will be to compare the Z-set navigation performance with that of other shipboard navigational aids. The TRANSIT terminal, LORAN-C, ship attitude reference, and the Z-set will provide to the data switch the data specified in Sec. 4.3 and Table 4-1. The data switch will fetch the data on an interrupt basis, process it, and store the quantities desired according to the predetermined set of conditions defined in Table 4-1. At specified times the stored data will be sent to the MARISAT terminal for transmission to the shore and further processing. All other data input to the computer will be entered manually. Comparison of GPS estimates of a ship's position and velocity with those of other systems will be accomplished ashore.

During the time between TRANSIT updates, the TRANSIT terminal output will indicate the ship's position and velocity based on the ship's log and gyrocompass inputs to the TRANSIT terminal. This mode will be referred to as dead reckoning. Two separate comparisons between GPS and TRANSIT will be made. One comparison will be the Z-set position outputs compared with TRANSIT position estimates at the TRANSIT update time, which

Table 4-1. Data Stored for Transmission to Shore (Cont.)

System	Timing	Data Stored
TRANSIT	GPS satellites not visible	TRANSIT data include latitude, longitude, Greenwich Mean Time, dead reckoning time, speed and heading, set and drift, course and speed of advance; sampled at a) Time of TRANSIT update b) Time when either speed or heading rate thresholds are exceeded c) At 1/2-hr intervals
	GPS satellites visible TRANSIT pass not in progress	1. TRANSIT data include latitude, longitude, Greenwich Mean Time, dead reckoning time, speed and heading, set and drift, course and speed of advance; sampled at a) Time when either speed or heading rate thresholds are exceeded b) 10-min intervals 2. Heading and course of advance rates at the 10-min sampling time
	GPS satellites visible TRANSIT pass in progress	1. Same as when TRANSIT pass is not in progress except sampling interval is changed from 10 min to 1 min 2. TRANSIT data include latitude, longitude, Greenwich Mean Time, dead reckoning time, speed and heading, set and drift, course and speed of advance; sampled at a) Start of TRANSIT pass b) Time of TRANSIT update c) End of TRANSIT pass 3. Maximum and minimum values of speed and speed of advance (along with heading and course of advance) over the TRANSIT pass interval 4. Heading and course of advance rates at time of TRANSIT update

Table 4-1. Data Stored for Transmission to Shore

System	Timing	Data Stored
Z-Set	GPS satellites not visible	No data
	GPS satellites visible TRANSIT pass not in progress	Z-set data include latitude, longitude, speed and bearing, estimated position error, and GPS time; sampled at 10-min intervals
	GPS satellites visible TRANSIT pass in progress	1. Z-set data include latitude, longitude, speed and bearing, estimated position error, and GPS time; sampled at 1-min intervals 2. Same data as specified above; sampled at the time of TRANSIT update
LORAN-C	GPS satellites not visible	No data
	GPS satellites visible	LORAN-C data include chain identification and time tags, latitude, and longitude; sampled at 10-min intervals
Ship Attitude Reference	GPS not visible	No data
	GPS visible TRANSIT pass not in progress	Pitch and roll angles and rates at the 10-min sampling intervals
	GPS visible TRANSIT pass in progress	1. Same as when TRANSIT pass is not in progress except 10-min sampling interval is changed to 1 min 2. Pitch and roll angles and rates at the time of TRANSIT update
All	As required	Discrete alarms

yields one data point for each TRANSIT pass during the time of GPS satellite visibility.

The second comparison to be made is the Z-set data with TRANSIT dead reckoning data, which will be made throughout the ship's voyage when the GPS satellites are visible. To obtain a LORAN-C and Z-set comparison, data will be taken throughout the ship's voyage when the GPS satellites are visible and LORAN-C is operational. Position comparisons between LORAN-C and the Z-set will be made. Velocity data will be extracted from the successive LORAN-C position fixes and compared with the Z-set velocity estimates.

During the ship's voyage it is expected that celestial position fixes and other fixes will be made as part of the normal ship operation. It is assumed that some of the fixes will be taken with instrumentation other than the Z-set, TRANSIT, or LORAN-C. These data will be time-tagged and manually entered into the computer through the teleprinter.

4.3 DATA REQUIREMENTS AND HANDLING

The data to be supplied to the data switch from the navigation systems will include the latitude, longitude, speed, heading, and any other parameter required to define the performance of the individual system. For example, the TRANSIT terminal, in addition to the parameters mentioned, would provide Greenwich Mean Time, dead reckoning time, set and drift, and the ship's present course and speed of advance. The data collected will be time-tagged and stored for later transmission to shore. The sampling rates recommended for the test consider the onboard memory storage requirements and the acceptable statistical confidence. This section developes the rationale for a sampling rate requirement and identifies the data switch processing

tasks, the data storage for transmission to shore, and the shore processing requirements.

4.3.1 Data Sampling Rates

The minimum sampling rate for data to be transmitted from ship to shore is set by the desired statistical confidence. The primary parameters to be examined ashore are position and velocity estimate differences. It is expected that the difference statistics will contain systematic and random components. The amount of data to be taken is a function of the desired confidence level in the estimate of the parameters to be extracted from the data. Since a plot of the cumulative distribution function of the differences is an excellent means of summarizing the data, the confidence level in the estimation of this distribution function will serve as the parameter on which the desired number of samples is based.

It is desired to draw confidence bands that are P percent about the estimated cumulative distribution function and such that, in the long run, these confidence bands constructed for random samples from the population will in 95 percent of the cases completely contain the population cumulative distribution function. Figure 4-2 shows the number of samples N versus P based on a nonparametric test. The choice of N is based on the desired P and is thus arbitrary.

In deciding on the amount of data for the demonstration, it will be assumed that all differences during one GPS visibility interval are random samples and that the desired P, from Fig. 4-2, is 25 percent for one GPS visibility interval. Thus the number of samples required is 30, which implies a data rate of one reading every 6 to 12 min. This rate will be specified exactly in the demonstration plan once the ship's course is

known. The data rate is assumed herein to be once every 10 min unless specified otherwise. Data from each navigation system will be sampled close enough in the sampling time interval to avoid the need for interpolation.

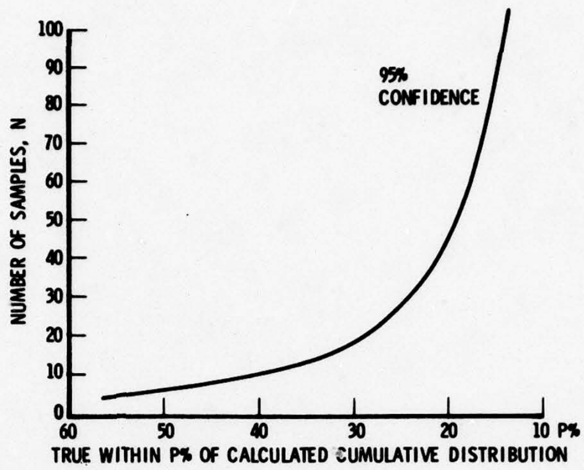


Fig. 4-2. Cumulative Distribution Curve for 95 Percent Confidence

4.3.2 Demonstration Processing Requirements

The demonstration processing requirements include the data collection and Z-set off-load functions and the shipboard display presentation (Sec. 5.4). The data switch will perform all shipboard processing tasks for the demonstration.

The data processing functions for storing the ship's course using the TRANSIT terminal outputs are shown in Fig. 4-3a. The TRANSIT data specified in Table 4-1 are stored for transmission during any period when the time rate of change of speed and heading exceeds preset values, at the time of TRANSIT update, every half hour when the GPS satellites are not visible, and every 10 min during GPS visibility.

Figure 4-3b shows that the LORAN-C data are time tagged and stored for transmission at a 10-min sampling rate. The Z-set

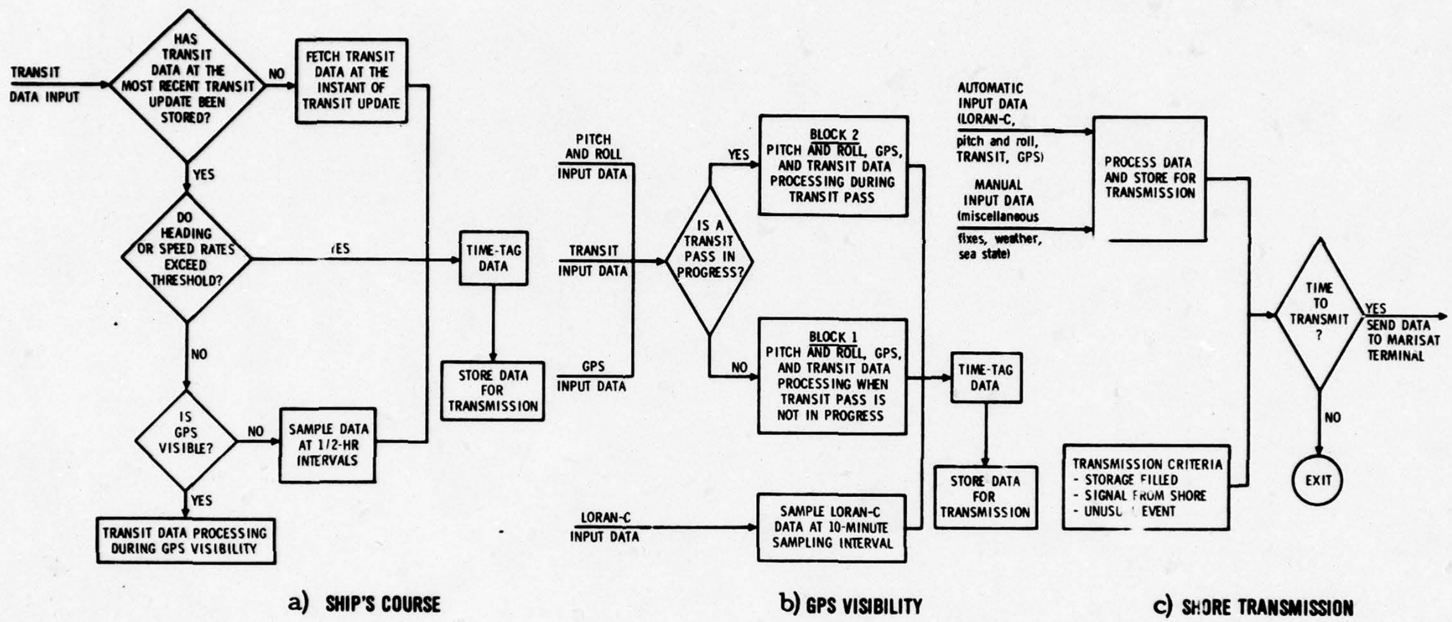


Fig. 4-3. Demonstration Processing Requirements

data, TRANSIT data, and ship attitude reference data are sent to Block 1 when a TRANSIT pass is not in progress. Block 1 computes attitude rates and samples the input data stream at a nominal 10-min rate. During a TRANSIT pass, the data from the Z-set, TRANSIT, and ship attitude reference are processed by Block 2. Block 2 processing is identical to Block 1 except that:

a. The data sampling rate is nominally one minute.

b. TRANSIT data at the start of the pass, for the instant of update, and at the end of the pass are saved.

c. The maximum and minimum values of TRANSIT speed and speed of advance and the corresponding heading over the pass interval are saved.

d. Z-set data as close as possible to the instant of TRANSIT update are saved.

Figure 4-3c depicts the data transmission logic. Selected automatic and manual input data are stored in the data switch dedicated memory locations for transmission to the shore. Data transmission will occur when the storage is filled on command from ship or shore or as the result of an unusual event, not less than once a day. The data transmission frequency and the definition of an unusual event will be specified in the demonstration plan. The automatic input data refers to the data and sampling rates given in Table 4-1. The manual data include sea state, weather conditions, bearing, and position fixes.

4.3.3 Data Stored for Transmission to Shore

Table 4-1 lists the data and gives the conditions under which the data from the navigation systems are collected and stored in the data switch for transmission to shore.

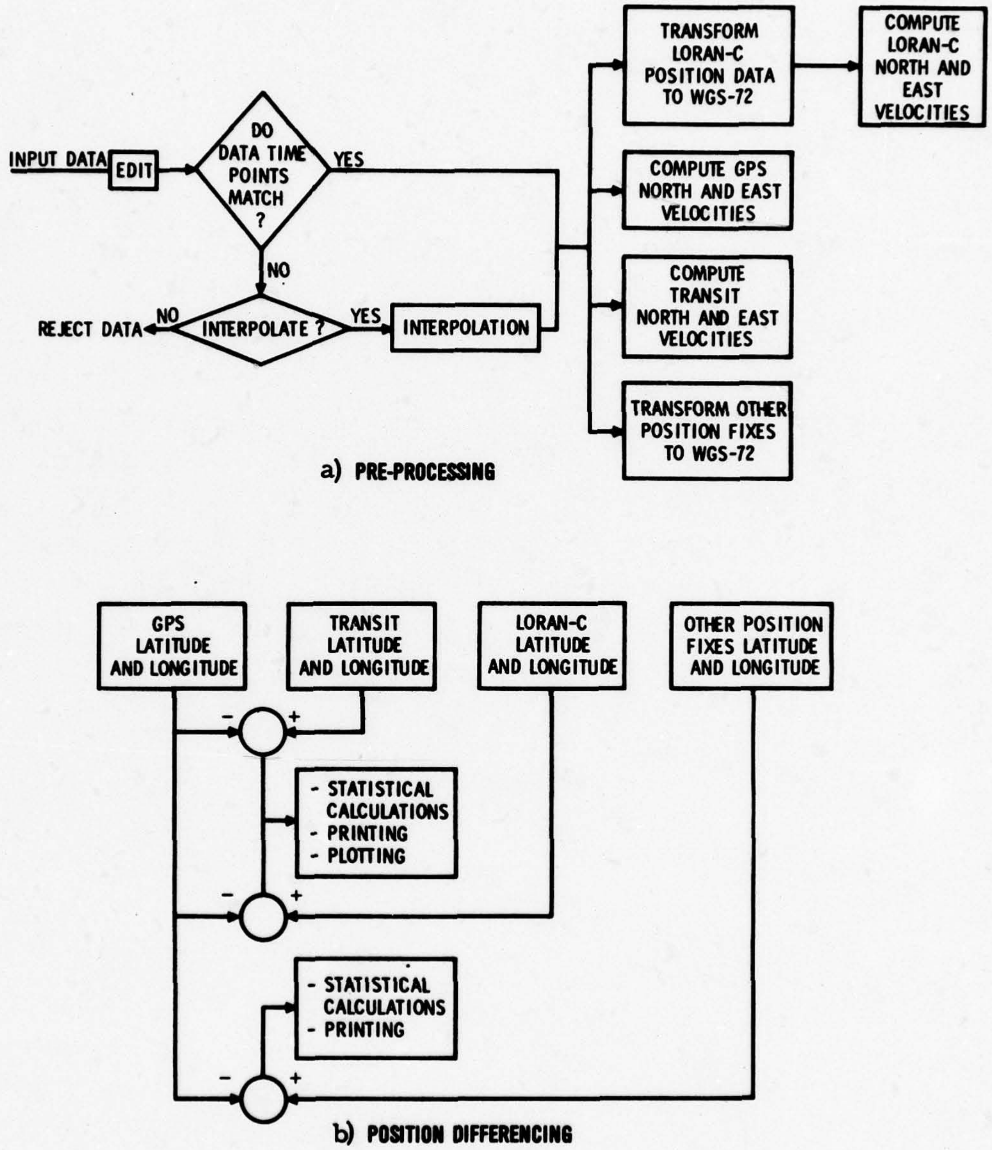


Fig. 4-4. Post-Test Shore Processing

4.3.4 Shore Data Processing

The shore data processor is basically a difference analyzer whose major function is to calculate and statistically summarize the differences among various navigation systems. Before calculation of differences, the received data must be preprocessed to edit the bad data, ascertain that the data are at the same time points, and transform the data to a reference geodetic datum (Fig. 4-4a). As indicated previously, it is expected that the data from each navigation system will be sampled close enough to the same time to avoid any need to interpolate. If the data time tags do not match within a specified tolerance, the data will be either rejected or interpolated. The next step is to transform the data as required to the WGS-72 datum (World Geodetic System). Position will be transformed to latitude and longitude, and velocity will be transformed to east and north components. TRANSIT and Z-set data already conform with respect to the WGS-72 system except that velocity data must be transformed to east and north velocities. LORAN-C position data are transformed to the WGS-72 system, after which the average velocity over the sampling interval is computed from successive LORAN-C position fixes. The block marked "transform other position fixes to WGS-72" (Fig. 4-4a) includes fixes from celestial fixes, bearings to landmarks, and charts. These fixes will probably be referenced to the local geodetic system, and each will require a different transformation to obtain position with respect to the WGS-72 system. Transformations from the geodetic to the WGS-72 system will be accomplished using the formulas in Ref. 3.

The transmitted navigation data from TRANSIT, Z-set, and LORAN-C will be the position and velocity of the antenna of the specific system. The transmission of the ship's attitude rate will allow transformation of these positions and velocities

to the ship's center of gravity should that become necessary. This transformation of the antenna motion to the center of gravity is not shown in Fig. 4-4a.

Figure 4-4b shows the flow chart of the simple position differencing that will be accomplished after pre-processing. Z-set latitude and longitude are differenced with latitude and longitude estimates from other systems (position differences will be transformed to north and east directions). The differencing to be accomplished ashore includes:

a. Z-set/LORAN-C position estimate differences

b. Z-set/TRANSIT position estimate differences at TRANSIT fix times

c. Z-set/TRANSIT dead reckoning position estimate differences

d. Z-set velocity estimate versus velocity estimate derived from LORAN-C position data

e. Z-set velocity estimate versus TRANSIT dead reckoning velocity estimates derived from the ship's speed log, gyrocompass, and estimates of set and drift

f. Difference between Z-set position estimates and estimates from bearing and position fixes

The Z-set/TRANSIT and the Z-set/LORAN-C differences will be plotted, and statistical calculations (rms, mean, and standard deviation) will be made over selected time periods or selected points. Z-set/other position fix differences will be printed, and any meaningful statistics will be calculated. The estimated cumulative distribution function of position and velocity differences over selected conditions will be calculated and plotted.

5. DEMONSTRATION SOFTWARE

The operating system and the routines and programs required for the demonstration software are based on the functional requirements defined in Secs. 3 and 4.

5.1. GROUND RULES AND REQUIREMENTS

The demonstration software encompasses the operating system and the routines and programs necessary to process the Z-set off-load functions, operate the shipboard display, and perform all demonstration functions automatically or manually. For this demonstration software, the following ground rules and requirements should be satisfied:

a. Modification of the Z-set resident software is not permitted for the demonstration.

b. None of the software routines need be re-entrant.

c. Comments must be embedded into the source language for each software module to identify its purpose and inputs and outputs.

d A set of mnemonics should define the variables, flags and parameters.

e. A brief description of each variable, flag and parameter must be included in the comment embedded in the software.

5.2 OPERATING SYSTEM

The operation of the demonstration equipment will be automatically scheduled and controlled by a real-time operating system resident in an HP 21MX computer. Since the functional requirements of the planned demonstration are beyond the capabilities of the data switch operating system, a baseline operating system that satisfies the demonstration requirements

is described here. This operating system may be implemented by modifying and upgrading the data switch operating system or (more probably) by using a Hewlett-Packard-supplied real-time operating system.

The operating system for the demonstration shall be able to service the I/O requirements of the interfacing navigation subsystems shown in Fig. 4-1 and to schedule the processing modules associated with the demonstration activities, including the CDU emulation and the Z-set off-load functions. Furthermore, the operating system shall have a scheduling executive to process these functional modules plus a separate structure to asynchronously handle the incoming data from the interfacing subsystems. The interrupt controls for each interfaced subsystem shall drive the I/O processing. The HP 21MX functional modules shall read data from and write data to buffer locations associated with each subsystem. The operating system should include:

a. Interrupt transfer vector
b. Individual interrupt handling routines
c. I/O drivers
d. I/O interface routines
e. Function scheduler
f. Operator interface control
g. Global data base

5.2.1 Interrupt Transfer Vector

The HP 21MX interrupt transfer vector must be loaded into consecutive memory locations. Each location corresponds to an I/O interface card and determines the priority associated with a specific I/O interface. In general, the I/O interface card and interrupt transfer vector address should be assigned according to the speed of interrupt response required by the interfacing navigation subsystem. All devices should be assigned in order of priority, with the highest priority going

to the privileged interrupts. After privileged interrupts are assigned, the next available slot should be given to the real-time clock interface. The remaining I/O interfaces required to implement the demonstration should then be assigned to subsequent locations in the interrupt transfer vector according to their priority servicing requirements.

5.2.2 Interrupt Handling Routines

An interrupt handling routine should be provided for each component of the interrupt transfer vector. To avoid the requirement for re-entrant software, the interrupt for that particular level should be disabled during the processing associated with the interrupt. Each interrupt handling routine should save the contents of registers that may be used by the interrupted routine. With the completion of interrupt processing at each interrupt level, the contents of the registers should be reloaded at the time of interrupt, the current interrupt should be re-enabled, and control should be transferred to the interrupted software location.

Most of the interrupt handling routines will involve servicing the I/O from the interfaced subsystems. These interrupt routines will differentiate between externally generated interrupts and the interrupts issued under program control (from the HP 21MX computer). This determination should be made by referring to an I/O communication list for each device. (I/O requests will set a flag within the list). The interrupt handling routine should inspect the I/O request flag and transfer it to the appropriate location within its corresponding I/O driver module.

In the case of computer service interrupts (power on/off, parity, etc.), the routines should reflect the demon-

stration requirements. The interrupt routine for the real-time clock should provide for the initialization and updating of memory locations representing a 24-hour clock and an interval timer. These clocks should have the resolution and format required to satisfy the demonstration requirements.

5.2.3 Input/Output Driver Routines

The individual I/O driver routines are responsible for data transfers between the interfacing subsystems and the HP 21MX computer. Each I/O subsystem and its driver routine have an I/O table that localizes and controls the information needed to operate the device and to communicate with the other elements of the demonstration software. The I/O driver routine should provide entry points for processing I/O in response to external interrupts and for I/O initiation and completion.

The physical input or output of data between the device and the computer will pass between the HP 21MX A or B register and the buffer register of the associated I/O interface card. The I/O driver software will format the HP 21MX output according to the requirements of the I/O interface. Correspondingly, the I/O driver will convert the input to the format required by the HP 21MX. Data input to the HP 21MX will be stored in the buffer region defined in the I/O communication table. Output data will be obtained in a similar fashion.

Each I/O driver should have a "time-out" clock. This clock acts to prevent an indefinite I/O suspension. This condition can occur when an I/O action is initiated and the device's controller fails to return a flag (possible hardware malfunction or improper program encoding). Without the controller time-out, the program which makes the I/O call would remain in I/O suspension, awaiting the operation complete

signal from the device's controller. The interfacing between the I/O driver routines and the demonstration modules will be provided by general purpose I/O interface routines.

5.2.4 Input/Output Interface Routines

The I/O interface routines will provide a high-level interface between the I/O driver routines and the navigation subsystems. The I/O interface routines should provide the capability to READ, WRITE, and STATUS any subsystem interfaced with the HP 21MX computer. The I/O interface routines should communicate with the requested device via the appropriate arguments entered as a part of a calling sequence. The arguments for the READ and WRITE routines should include the device identifier, I/O list, and number of words in the list. In addition to the device identifier argument, the STATUS routine should have arguments for I/O valid flag and complete flag.

5.2.4.1 Operating Requirements

The READ routine should transmit the number of words of information from the I/O buffers of the selected navigation subsystems and place it in the appropriate memory locations of the HP 21MX. The READ routine, which depends on the I/O communications characteristics of the subsystem, may invoke an I/O operation or assume that the actual I/O has been completed by an asynchronous interrupt. The WRITE routine should perform in a similar fashion. For the most part, the WRITE routine should transmit the number of words of information from the navigation subsystems to its assigned I/O buffers. The WRITE routine should initiate the output operation and return control to the user function. The STATUS routine should return to the user the status of the I/O valid and I/O complete entries.

5.2.5 Function Scheduler

The function scheduler provides the mechanism for scheduling any functional process of the demonstration software on the basis of an input or an internally generated list of scheduled events. Actually, the scheduler should monitor two lists of events: The first list, which should be input during the demonstration initialization, should specify the time of the event and the function to be invoked at that time. (Care should be taken to ensure that the event times are synchronized with the system real-time clock). The second list should contain the events to be scheduled on request from one of the functional processors. For example, the LORAN-C data collection processor may reschedule after some given time interval via a system subroutine that adds an internally scheduled event for the function specified.

These two event lists should have the same format; the only difference should be in the method of entering events into and selecting events from the lists. A dual entry should indicate the event time and the corresponding function name to be scheduled. The event times should be compatible with the 24-hour real-time clock. The address communication table should reflect the relative priority of the given function, with the highest priority given to the first entry. In the event that two or more functions are scheduled simultaneously, the scheduler should dispatch the function with highest priority first. If two functions with the same priority are scheduled simultaneously, the scheduler should dispatch the functions according to their detection in the event list. Events should be added to either of the event lists using the scheduler subroutine. In the event that no activities are to be scheduled, the scheduler should enter a loop that continuously looks for and reacts to inputs from the operator input device.

5.2.6 Operator Interface Control

The operator interface control should provide the following basic features:

a. System initialization
b. Operational test control
c. System checkout control
d. System debug control
e. On-line data base modification
f. System completion control

5.2.6.1 System Initialization

The system initialization should contain the initial entry point for the demonstration software. It should disable all interrupts except for power-fail and provide the capability to restore memory to a state that will allow the system to restart without reloading. Pertinent locations in the data base must be initialized to the specified values, necessary information must be requested from the operator, operator inputs must be processed, and the system must in general be made operational (ready mode). When the initialization is complete, the computer should issue an action query to the operator, and the software should compare the operator response with a known action table.. System action queries should be identified as special operator inputs. The software should respond to the indicated actions until the operator issues the operational start test response. On receipt of this input, the initialization module should enable the pertinent interrupts and transfer control to the demonstration function scheduler.

5.2.6.2 Operational Test Control

This software module should be invoked by the demonstration function scheduler in the background mode. At any

time during an operational test, the operator may request any of the available system action procedures.

5.2.6.3 System Checkout Control

This module should control the operation of any features built into the demonstration software to perform automated system checkout procedures.

5.2.6.4 System Debug Control

This feature should allow the dumping of input specified memory locations in a format that will be useful for diagnostic purposes. In addition, it should be entered to provide a background feature in the operational mode to output selected information to the operator console on a scheduled basis.

5.2.6.5 On-Line Data Base Modification

This module should be invoked primarily during the system initiate action phase. This is a flexible method for last minute nonstandard changes to the system data base.

5.2.6.6 System Completion Control

This function is intended primarily to perform all of the necessary checkpoint activities required to complete or halt the operational tests.

5.2.7 Global Data Base

The demonstration software should be designed to provide a global data base to the greatest extent possible. This data base should occupy contiguous locations subject to the

constraints of memory paging, functional grouping, word-size variations, and reservations for future expansion. The global data base should contain all the needed system flags, parameters, variables, tables, and I/O buffers.

5.3 COMPARISON OF OPERATING SYSTEMS

The operating system described in Sec. 5.2 satisfies the demonstration functional requirements and provides a baseline for the qualitative comparison of the development cost and schedule and the reliability of operation of the data switch and HP RTE-M operating systems.

5.3.1 Z-Set Demonstration Configuration

At the technical interchange meeting of 28-29 June, 1978, the demonstration requirements for real-time transmission of data from ship to shore were deleted. Figure 5-1 shows the Z-set demonstration configuration without this requirement. This configuration records the collected data on a cassette and provides hardcopy at the navigator's request. Except for the navigation subsystems, the configuration consists entirely of off-the-shelf Hewlett-Packard equipment to minimize the cost of hardware modifications and software development. The HP 2112B computer has been substituted for the data switch (HP2108B) in this configuration, which eliminates the requirement for an add-on memory module, increases the available number of I/O channels from 9 to 14, and saves $2,600. The HP 2112B, with 128K bytes of memory, has sufficient capacity for the operating system and the demonstration software (with the HP 2108B, all available I/O channels are occupied, which might restrict the ability to make last-minute changes to the configuration). The shipboard display is the HP 2645A, an adequate substitute for

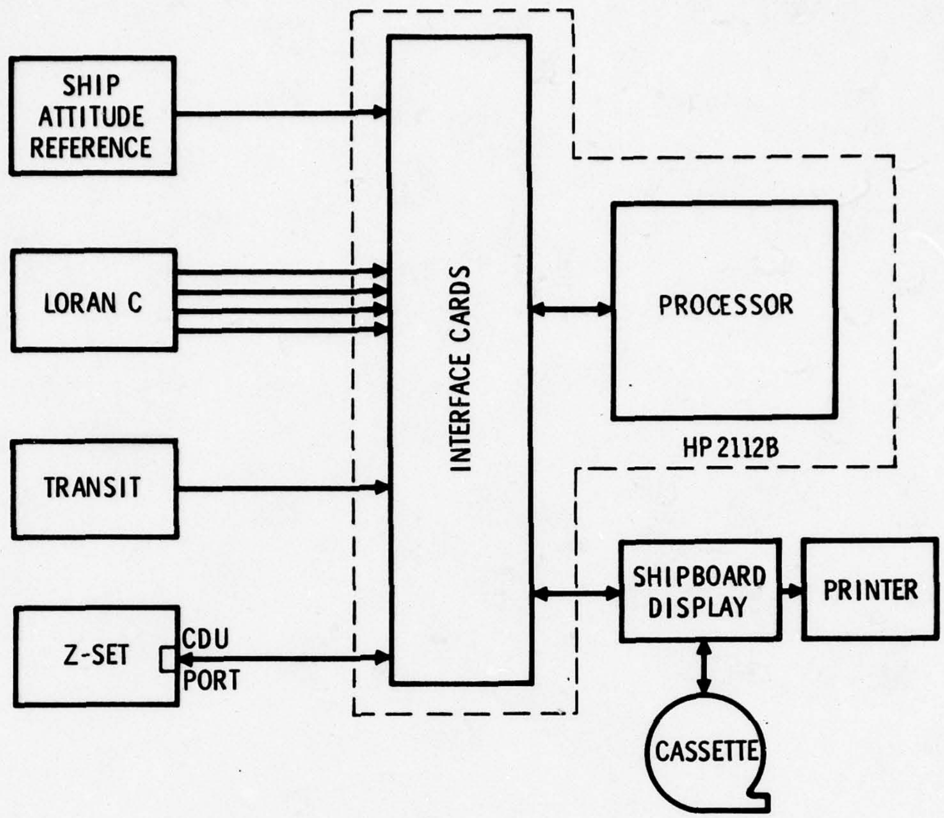


Fig. 5-1. Demonstration Configuration

the Beehive B-500 or the Delta Data 4500 when no computational features are needed, as is the case for the proposed demonstration configuration (Fig. 5-1). The HP 007 cassette provides on-board mass storage for loading the operating system and the demonstration software, and the HP 9866A provides hardcopy capability. The HP 007 is a dual cartridge tape recorder with a capacity of 110,000 characters, which is sufficient storage to limit cartridge replacement to every three to five days. Table 5-1 specifies the required Hewlett-Packard interface cards for each navigation subsystem and gives an approximate cost for these cards and the Hewlett-Packard equipment identified in Fig. 5-1.

Table 5-1. Demonstration Equipment

Item	HP Equipment or Interface Card No.	Cost (Approx) $	Remarks
TRANSIT	HP 12531D	350	
LORAN-C	HP 12554A	1,400	4 required (may be substituted for a multiplexer card)
Ship Attitude Reference	HP 91000A	1,600	A/D converter
Z-Set	HP 12531D	350	CDU port
Time Base Generator	HP 12539C	350	
Computer	HP 2112B	6,200	
Cassette	HP-007	1,600	
Shipboard Display	HP 2645A	3,500	
SD Interface	HP 12966A	600	
Thermal Printer	HP 9866A	3,350	Teletype substitute
Misc. Accessories		1,000	
Total Cost ($)		20,300	

Table 5-2 presents a qualitative comparison of the data switch and the HP RTE-M operating systems measured against the baseline operating system described in Sec. 5-2. For the one-time demonstration, it is apparent from the matrix of operating system features that the Hewlett-Packard RTE-M will provide the best performance in terms of cost, program schedule, and reliability of operation, but it may require some modification. Standard maintenance packages and Hewlett-Parkard personnel are available here and at several foreign ports to service the equipment.

Table 5-2. Operating Systems Comparison

Features	Baseline	TDS	HPs RTE-M
Coding Language	As chosen	Assembler	Object code
Development Schedule	6-9 months	6-9 months	2-3 months
Maintenance Software Package Available	None	None	Yes - software subscription service at $50/mo
Development Cost (approx)	$200K	Unknown - appears to be 80-90% of baseline	$25K
Advantages	Tailored to application	Teletype interface already written	Cognizant programming staff available at HP or OEM
Disadvantages	No maintenance continuity if original programmers leave	Lacks maturity - one of four tests complete to date Developed for simpler processing tasks	Increases memory requirements

5.4 SOFTWARE TASK

The demonstration software requirements demand an operating system considerably more extensive than the MARAD data switch (Ref. 4). This complexity results from the large number of interfacing subsystems, the routines and programs required to process Z-set off-load functions, and the CDU emulation and data collection functions.

The mechanics of the software task are greatly reduced given the availability of a HP 2112B computer using the RTE-M operating system. Such a system provides the software development personnel with the facilities to quickly develop source program modules, compile or assemble them, edit, copy, and change program modules. To minimize the software task development costs, all the available Hewlett-Packard software modules should be reviewed for possible use, especially for the I/O

drivers, arithmetic routines, and display formats. The demonstration software development philosophy should be that it is generally cheaper and more efficient to obtain or purchase existing modules.

The software that must be developed should be programmed for the FORTRAN language compilers provided by Hewlett-Packard. Software not amenable to development in FORTRAN must be prepared in assembly language with linkage compatible with the FORTRAN-generated software. Each module or subroutine that is prepared as a part of the demonstration software should be described on comment cards, which should define all linkages to other subroutines or modules. Each variable or parameter that is passed to the routine and that the routine passes to other portions of the software should be defined. Finally, any special processing methods or assumptions the routine uses should be described.

The demonstration software that requires development are the Z-set off-load functions, shipboard display, and data collection. The two Z-set functions performed externally are the digital filter for smoothing out the velocity information before presentation on the shipboard display (Sec. 6.3.3.2) and the calculation of the estimated time of arrival for any way-point. The shipboard display function emulates the Z-set CDU and provides software substitution for the CDU panel switches. The data collection functions include the assembly and storage of the data from the navigation subsystems at the rates and for the conditions defined in Table 4-1, dead reckoning navigation during periods of no GPS satellite coverage, automatic Z-set initialization once satellite coverage is re-established, and operator interaction with the demonstration equipment via the shipboard display keyboard.

The details of the data collection processing and logic for the navigation subsystems are defined by the flow charts presented in Appendix A. The TRANSIT terminal interfaces are assumed to operate in an asynchronous manner. Data will be transferred across the terminal interface under interrupt control. The data will be formatted to the requirements of the HP 2112B computer and stored in buffer memory. For TRANSIT, the function must approximate the ship's speed and heading rates to initialize the data collection functions. To provide for these approximations, the TRANSIT data collection function will be scheduled at regular intervals. This interval should not be so small that it will create throughput problems for the computer; a recommended default interval is one minute. Similar processing requirements apply for the LORAN-C, the ship attitude reference, and the Z-set.

After the initial software development, the demonstration hardware/software configuration shown in Fig. 5-1 should be checked out in the laboratory with as much realism as possible. The laboratory results should be recorded and used to validate equipment operation after the shipboard installation.

6. Z-SET ERROR SOURCES AND SHIPBOARD NAVIGATION PERFORMANCE

Computer simulations were run to evaluate Z-set navigation performance under the conditions anticipated for the at-sea demonstration. The objectives were to:

- Examine Z-set navigation performance and its response to the effects of heavy seas and ship maneuvers
- Study the antenna lever arm effects on the velocity data
- Evaluate Z-set navigation performance with only three satellites.

The simulation assumed a typical merchant ship sailing out of Long Beach during the early satellite availability period of the Phase I constellation. The magnitudes of the maritime user error sources were estimated from ongoing field work and computations made on the Z-set measurement models.

This section discusses the method of simulation, defines the primary error sources affecting Z-set measurement accuracy, describes the simulation performed, and identifies functional changes to the Z-set needed for the at-sea trials based on the simulation results.

6.1 SIMULATION METHOD

The ship simulation used the Navstar User Simulation (NUSIM) program, which forms part of The Aerospace Corporation's GPS test bed simulation. NUSIM performs the correlated dependence of the error sources identified in Table 6-1 and projected through the satellite geometry. This magnification for range measurement accuracy is expressed by Z-set

Table 6-1. Estimated Z-Set User Equivalent Error (one-sigma)

Error Sources	Range Error, ft	Range Rate Error, ft/sec
Satellite ephemeris	12	-
Satellite clock	8-50	-
Z-set receiver/processor	45	0.2
Multipath	4-50	-
Atmospheric delay:		
Ionospheric	13-40	-
Tropospheric	7-15	-
RSS (1 σ)	50-95	0.2

Kalman filter computations and generates plots of the estimation of the navigation errors using data from two input tapes that supply the ship's track and motion, simulated measurements, true measurement values, and satellite ephemeris data. The simulated measurements are the geometric values corrupted only by the Z-set clock errors. NUSIM further corrupts the data by Monte Carlo techniques prior to Kalman filter processing. The measurement error model in NUSIM includes bias, colored and white noise errors for the pseudo range measurements, and white noise errors for the pseudo range rate measurements (hereafter referred to as delta range measurements). The values used are intended to represent the composite effects of the error sources from the satellite ephemeris and clock, atmospheric propagation delay, and Z-set receiver/processor measurement accuracy. Figure 6-1 shows a simplified block diagram of the user tape/NUSIM measurement sequence for maritime applications of the Z-set. A detailed description of the NUSIM block diagram is given in Sec. 6.2.2.5.

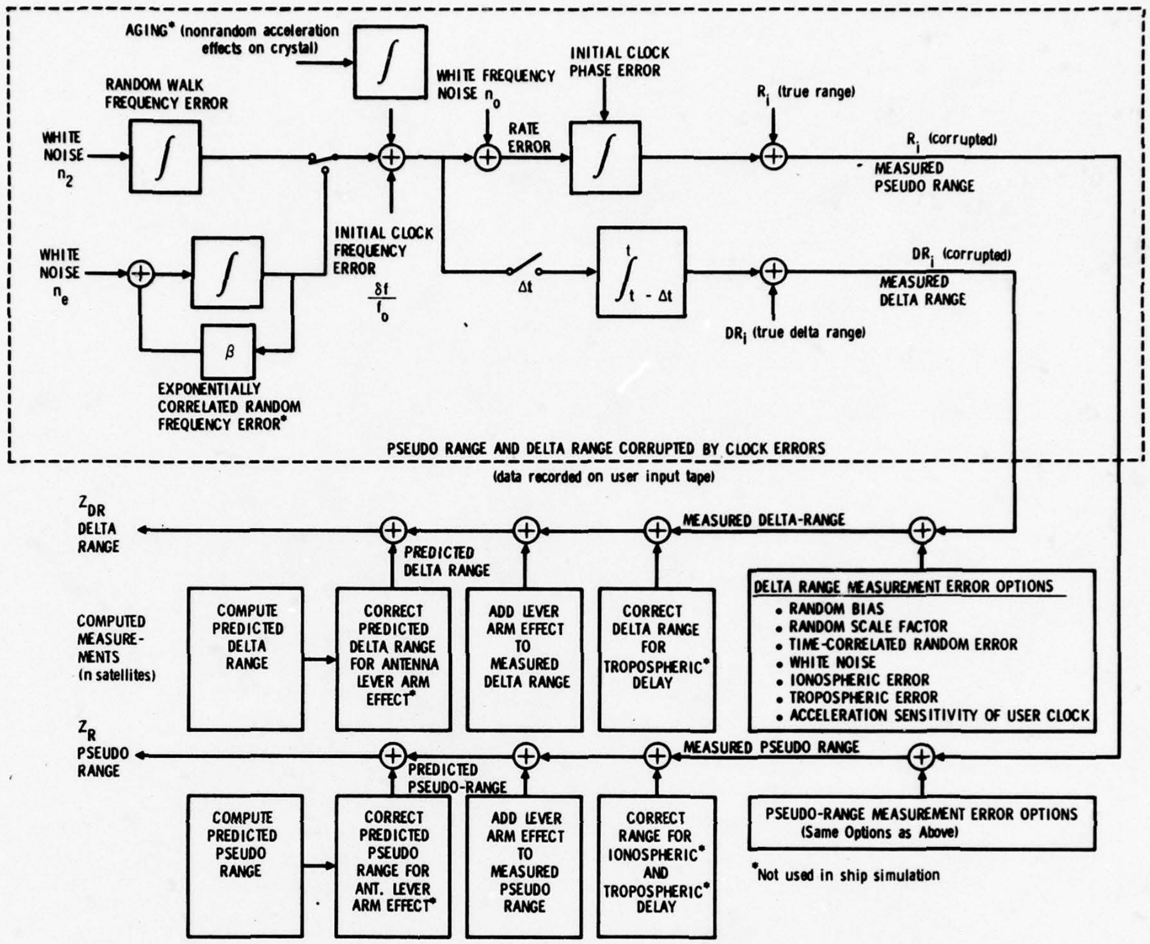


Fig. 6-1. Navstar User Simulation

6.2 Z-SET MEASUREMENT ERROR MODELS

The primary error sources for the Z-set user include satellite ephemeris and clock stability, Z-set receiver/processor measurement accuracy, multipath effects, and atmospheric delays from the ionosphere and troposphere. Table 6-1 provides an estimate of the Z-set user equivalent range and range rate errors. All values represent one-sigma errors.

Z-set navigation accuracy is a function of the goodness of the user-satellite geometry multiplied by the user equivalent range errors. Mathematically, this accuracy has been defined as the estimated statistics of the magnitudes of the error sources in the Z-set user position vector, where the estimate of these errors contains the geometric dilution of precision (GDOP) performance index. Besides amplifying the pseudo range measurement errors, the GDOP index provides a criterion for designing satellite constellations independent of any coordinate system. It is basic to any satellite selection criterion.

Mathematical definitions of error sources that affect the measurement accuracy of the Z-set range and range rate follow. Filter noise vector elements and the development of the truth models for the Z-set measurement errors are also discussed.

6.2.1 Filter Measurement Noise

The filter measurement noise equations account for the corruption of the relationship between the measurement residual and the linearized state vector. The measurement residual is given by

$$\bar{z} = \bar{Z}m - \hat{\bar{Z}} \qquad (6\text{-}1)$$

where

$\bar{Z}m$ = observed vector

$\hat{\bar{Z}}$ = computed vector

The measurement sensitivity matrix is represented by

$$\bar{h} = \left.\frac{\partial \bar{z}}{\partial \bar{x}}\right|_{\bar{x} = \hat{\bar{x}}} \qquad (6\text{-}2)$$

where the error in the navigation state

$$\bar{x} = \hat{\bar{y}} - \bar{y} \tag{6-3}$$

i.e., the computed minus the true navigation state is used in the linearized measurement equation

$$\bar{z} = \bar{h}\bar{x} + \bar{v} \tag{6-4}$$

Here $\bar{v}$ is the measurement noise vector, which is assumed to be white, normally distributed with zero mean, and of covariance R. It is desired that $\bar{v}$ account for unmodeled or imperfectly modeled measurement effects; thus, for pseudo range the noise variance is computed as

$$E\,\bar{v}_{PR}^2 = \sigma_{PR}^2 = \sum_{i=1}^{n} \sigma_i^2 \tag{6-5}$$

where i(1,n) signifies independent measurement errors and includes lever arm, ionospheric, tropospheric, multipath, satellite position and clock, user clock, receiver tracking, and other miscellaneous errors. A similar equation is used for delta range measurement errors σ_{DR}.

6.2.2 Truth Models

Truth models form the basis for software compensation of measurement errors and, in simulation, provide the means of estimating the navigational errors incurred by omission or imperfect compensation for the measurement errors. The following truth models correspond to the filter measurement errors discussed above.

6.2.2.1 Lever Arm

A lever arm effect occurs if the antenna location and the ship's center of gravity do not coincide. The antenna displacement from the center of gravity and the angular rotation about it enter into the calculation. The displacement or lever arm may be represented as

$$\bar{\ell} = \bar{U}\bar{\ell}_B \tag{6-6}$$

where

$\bar{U}$ = direction cosine matrix, body-to-earth-centered coordinates or body-to-tangent plane

$\bar{\ell}_B$ = lever arm in body frame, right-hand system: roll axis, left wing up (m)

The effect on pseudo range may be computed by taking the dot product of $\bar{\ell}$ and the unit range vector to the appropriate satellite.

The antenna velocity may be expressed by

$$\bar{v} = \bar{v}_o + \bar{\omega} \times \bar{\ell} \tag{6-7}$$

where

$\bar{v}_o$ = translational velocity of the vehicle center of gravity (m/sec)

$\bar{\omega}$ = angular rotation of the antenna about the vehicle center of gravity in earth-centered coordinates (rad/sec)

The contribution of the lever arm term $\bar{\omega} \times \bar{\ell}$ to delta range may be computed by dotting $(\bar{\ell}_2 - \bar{\ell}_1)$ with the unit range vector.

In the ship simulation these errors can either be included in the user tape measurement data or superimposed by the NUSIM program. The latter provides greater flexibility since $\bar{\ell}_B$ can be changed without changing the user tape.

6.2.2.2 Ionosphere

The ionospheric time delay equation can be expressed by

$$\Delta\tau(E) = 12 \frac{L}{h_2 - h_1} \pm \sigma(E) \quad (6\text{-}8)$$

where the variance of $\Delta\tau(E)$ is

$$\sigma^2(E) = (8.9)^2 \left[\frac{L}{h_2 - h_1}\right]^2 + (1.7)^2 \frac{L}{h_2 - h_1} \quad (6\text{-}9)$$

and where h_2 and h_1 are the upper and lower heights of the slab representation of the ionosphere, L is the radio path length within the ionosphere, and E is the elevation angle above the horizon.

A reasonable approximation of Eq. (6-8) in the mean square sense is given by the expression

$$\Delta IONO = \frac{13}{\sin\left[E^2 + 0.1\right]^{1/2}} \quad (6\text{-}10)$$

where E is in radians and ΔIONO is in nanoseconds or feet.

The delta range measurement is subject to change in the ionospheric delay only during the integration time (0.5 to

1 sec). The ship simulation program incorporates the delay expressed by Eq. (6-10) into the pseudo range measurement at each cycle. An input parameter specifies the numerator.

6.2.2.3 Troposphere

The tropospheric delay (sec) may be expressed by

$$\Delta TROPO = \frac{1}{c} \int_S^U \eta \, ds \qquad (6\text{-}11)$$

where η is the local refractivity, c is the speed of light, and ds is the differential path length along the transmission path between the satellite and the user. An exponential atmosphere is assumed such that

$$\eta = \eta_o \exp(-H/H_s) \qquad (6\text{-}12)$$

where η_o (3.2×10^{-4}) is the sea-level atmospheric refractivity and H is the user altitude. H_s is the exponential scale height (assumed to be 6900 m). The expressions for tropospheric delay assume a flat earth. Integrating Eq. (6-11) for different satellite and user altitudes yields

$$\Delta TROPO = C \exp(-H/H_s) \qquad (6\text{-}13)$$

$$C = \mathrm{Min}\,(C_z/\sin E,\ 86.3) \qquad (6\text{-}14)$$

Here

$$C_z = \eta_o H_s = 2.21 \qquad (6\text{-}15)$$

is the delay (in meters) for a satellite at the zenith and a user at zero altitude.

The ship simulation program incorporates the tropospheric delay error, Eq. (6-13), into each pseudo range measurement. The tropospheric delay effect on the delta range may be included, but the error is small since it applies only to the delay changes over the delta range integration interval. The Z-set software compensates for the tropospheric delay effect on the pseudo range measurements.

6.2.2.4 Multipath

To experience the multipath effect, both the direct and reflected rays from the satellite must impinge on the user antenna at an angle within its effective power pattern. If, for an unstabilized antenna, coverage is defined by a given half-cone angle, multipath errors can occur only when certain combinations of satellite azimuth and elevation angles and ship heading, roll, and pitch angles exist.

These conditions are met if the satellite elevation angle plus the maximum zenith angle for satellite use is equal to or greater than 90 deg. They are also met if the angle between the antenna boresight line and the LOS to the satellite and the angle between the antenna boresight and the multipath reflection are both less than the half-cone angle. The surface interaction multipath variables needed to determine user position error e from the appropriate Z-set discriminator function are the ratio a of the multipath signal amplitude to the direct LOS signal amplitude and the time delay δ_m of the surface multipath component relative to the direct LOS component. A useful approximation for δ_m for maritime applications where the user altitude H is small relative to satellite altitude is given by

$$\delta_m \approx 2H \sin E \qquad (6\text{-}16)$$

The expression for the attenuation factor a reduces to

$$a = (\rho_{11}{}^2 = \rho_{\perp}{}^2) \; \frac{A_{mp}}{A_{\ell s}} \cdot \frac{F_{mp}}{F_{\ell s}}^{1/2} \qquad (5\text{-}17)$$

where

$\rho_{11}, \rho_{\perp}$ = orthogonal plane surface reflection coefficients

A = capture area of the user antenna

F = polarization efficiency

with mp and ℓs designating multipath and LOS, respectively.

The pseudo range error e corresponding to given values of a and δ_m oscillates between the limits of the discriminator function shown in Fig. 6-2. The change in e from plus to minus is rapid for small changes in δ_m since the carrier period corresponds to only 0.6 ft.

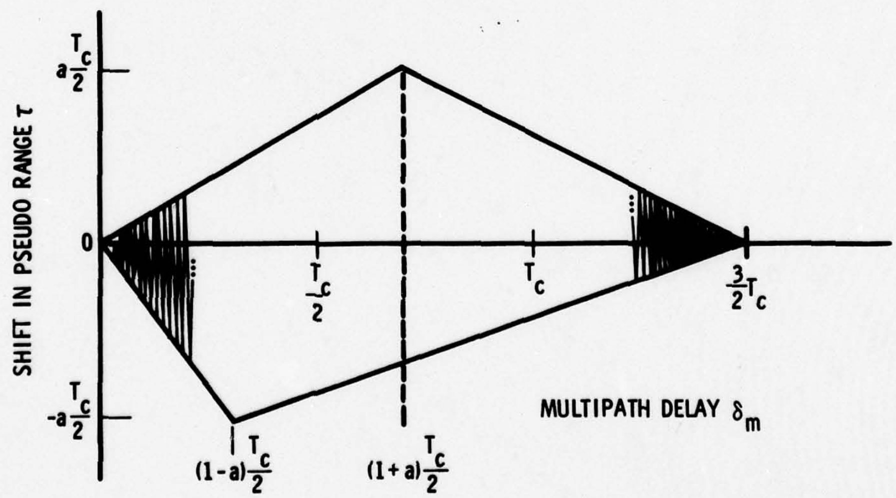


Fig. 6-2. Code Loop Response to Static Multipath Interference

The preferred approach to modeling e assumes that for each set of values (a, δ_m) e is uniformly distributed between the upper and lower limits of the Z-set discriminator function. In this approach, a random number g with equal probability between 0 and 1 is selected at each measurement time. This random number g is then multiplied by the difference between the limits of the discriminator as determined from the calculated values of a and δ_m, and the result is added to the lower limit to yield e.

The multipath induced by the ship structure may be considered a special case of the above development where the earth's surface is replaced by the reflecting surfaces of the structure.

Because of the symmetry in the envelope of the carrier shift time $\Delta\tau_f$ as a function of δ_m and the relatively fast change in δ_m, the average delta range error due to multipath will tend toward zero.

The carrier-to-noise ratio degradation arising from atmospheric (tropospheric and ionospheric) multipath propagation can be translated into pseudo and delta range errors by dividing the receiver code tracking and carrier errors by the square roots of the resulting signal-to-noise ratios. However, these errors are generally neglected in analysis since they are concerned with effects that are highly probabilistic and, for satellite elevation angles above 15 deg, the error magnitudes are adequately offset by the system's gain margin.

The NUSIM test bed simulation did not have the multipath effect option for pseudo range measurements; therefore, this error source was not part of the ship simulation. However, it could be readily implemented into the simulation in future studies.

6.2.2.5 Clock, Satellite Position, and Receiver Tracking

The remaining error sources are due to the satellite clock accuracy and stability, user clock phase and frequency, and position and receiver tracking.

A widely used measure of frequency stability in the time domain is the fractional frequency stability $\sigma\Delta f/_f$, which is defined as the ratio of average frequency error to mean frequency as measured by counting the cycles or cycle increments elapsed during an averaging time τ and taking the root mean square of many such observations. The fractional frequency stability is also referred to as the square root of the two-sample Allan variance, in which case it is generally designated $\sigma_y(\tau)$.

For a given clock, the expected error of measuring a time interval τ is related to the clock error fractional frequency stability by

$$\sigma_T = \tau \cdot \sigma_y(\tau) \qquad (6\text{-}18)$$

A useful property of the Allan variance is the existence of a power law type of relationship between the variances and spectral densities of the noise types known to affect time standards. This relationship is depicted in Fig. 6-3 for the three noise types defined by regions I, II, and III. The adequacy of representing the satellite clock noise processes by one or more of these three independent models has been confirmed experimentally (Ref. 5). These functional relationships are important because a knowledge of the time domain stability of an oscillator can be used to determine the spectral level of the driving noises in a time standard error model.

Behavior in the short-term stability region (I) corresponds to white frequency noise and may be due to circuit noise in quartz crystal oscillators, shot noise in beam tubes (cesium standards), or light intensity variations in optical devices (rubidium clocks). It is emphasized that a specified behavior may or may not occur in a given standard. Behavior in regions II and III is thought to be due to the effect of correlated influences on the standards, (e.g., voltage fluctuations in power sources, magnetic field fluctuations, and systematic changes). The flicker noise characteristics may be observed in all the GPS time standards of interest. Note that the flicker level changes are due to variations in the environment. The random walk frequency drift in region III may be observed in both quartz oscillators and rubidium standards.

The effect of pure frequency drift (linear aging) is displayed in Fig. 6-3. Although it is not defined as an Allan variance, the frequency drift may be a significant source of error in quartz and rubidium devices if the sampling time is long enough and if the clock frequency is not estimated.

Techniques for translating the sigma-tau characteristics of a specific clock model into a time domain model for purposes of simulation have been described (Refs. 5 and 6). Modeling the flicker frequency behavior, however, is difficult since the power spectral density ($1/|\omega|$) cannot be realized by a finite dimensional linear system. This problem can be circumvented by approximating the needed $s^{-1/2}$ transfer function by a cascaded series of lag-lead networks (usually at least two), whose input is a computed level of white noise.

The NUSIM program provides considerable flexibility in truth modeling of clock phase and frequency errors. This part of the NUSIM program is represented schematically in Fig. 6-1.

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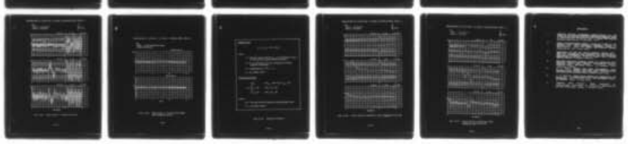

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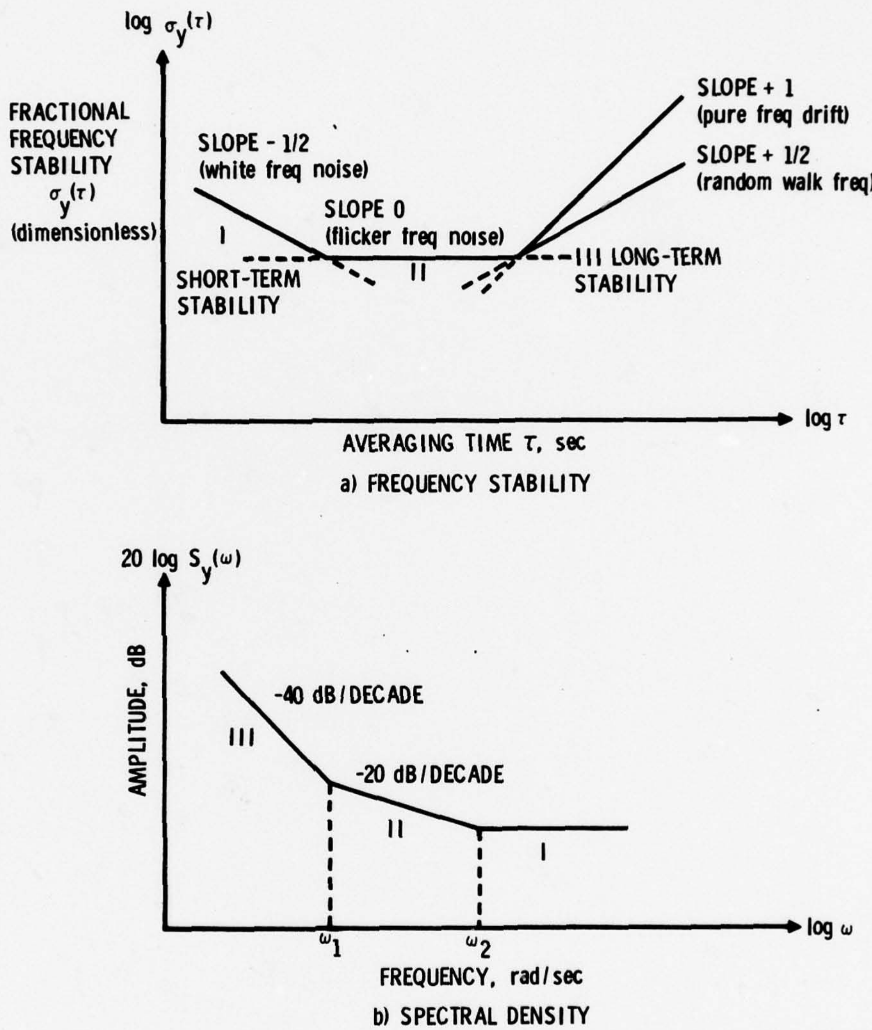

Fig. 6-3 Clock Stability

The area inside the dashed lines simulates the corruption of delta and pseudo range measurements by the user clock phase or frequency errors. The user data tape provides this input and can accommodate errors of the following types: white frequency rate noise (random walk frequency error); time-correlated random frequency (Markov process); nonrandom aging; deterministic or random constant frequency or phase errors; and white frequency noise. These effects can be combined as desired. Although no model corresponding to flicker noise is presently included, this characteristic, if needed, can be approximated by using one or more of the noise types available. Alternatively, real receiver delta range and pseudo range data can be recorded and utilized as a tape input to the simulation. It is common practice to model the user clock frequency and phase errors as states in a Kalman filter estimator (often as time-correlated random walk processes) to minimize the effect of user clock errors on navigation accuracy.

The lower portion of Fig. 6-1 shows additional options for simulating corruption and compensation of delta and pseudo range errors by measurement and propagation errors. The pseudo range errors introduced are intended to be uncorrelated with the delta range errors; however, correlation can be obtained by properly setting up the simulation parameters. For example, a white frequency noise source produces a random walk phase error, and both of these error sources are available as options. Correlated errors of this type would generally be simulated as a tape input.

The measurement error options available are useful for insertion of user carrier and code tracking errors, quantization, satellite ephemeris and clock errors, and other miscellaneous errors. These errors are conveniently modeled as random constants, random scale factors, white noise source

errors, or exponentially correlated random errors. The random constant and scale factor errors are randomly selected for each satellite from a subprogram once at the beginning of a simulation. In the white noise or exponentially correlated random error options, the subprogram is entered once each measurement cycle. Initial phase and frequency errors for the satellite clocks can be introduced as random constants based on values selected from the specified clock fractional frequency characteristics.

6.3 SIMULATION OF SHIPBOARD USER REQUIREMENTS

The simulation of the Z-set performance for shipboard application was obtained by reproducing the expected nominal and maximum at-sea conditions during Phase I satellite coverage and from a set of measurement errors for the Kalman filter.

6.3.1 Simulation Setup

The input tape to the NUSIM program for satellite ephemeris uses the orbit parameters for the Phase I constellation (Table 6-2). In the North Pacific, between Long Beach and Hawaii, three or more satellites are available for about 6 to 7.5 hr daily, and four or more satellites are available for about 5 to 6 hr. To limit atmospheric propagation delay errors, only satellites more than 5 deg above the horizon are employed.

The simulation used two ship tracks, one with four or more satellites in view early in the period of satellite availability and the other late in the period when only three satellites are available. Track 1 is for a ship steaming west at 20 knots out of Long Beach Harbor. The time period is from -1.25 to -1.00 hr, and zero time corresponds to the orientation of

Table 6-2. Navstar Global Positioning System Phase I Orbit Configuration

Satellite No.	Period, sec	Inclination, deg	Right Ascension of the Ascending Node,[b] deg	Mean Anomaly,[c] deg
1	43,078.26	63	240	-29
2	43,078.26	63	240	14
3	43,078.26	63	240	56
4	43,078.26	63	120	18
5	43,078.26	63	120	61
6	43,078.26	63	120	103

[a]All satellites have orbits with both eccentricity and argument of perigee = 0.

[b]Referenced to 21 March 1977.

[c]Referenced to midnight GMT on 21 March 1977, when the right ascension of the prime meridian was 178.4 deg.

the satellites as indicated in Table 6-2. For convenience, this configuration references zero time to midnight Greenwich Mean Time on 21 March 1977. Track 1 begins at the time of the best GDOP for this location; five satellites are available (Nos. 1, 2, 3, 5, and 6). The ship proceeds west for 10 min, turns at a rate of 3 deg/sec, and steams south for 5 min. Nominal sea conditions are considered to exist for the first 5 min, followed by extreme sea conditions for the next 10 min.

Track 2 is similar to track 1 but occurs late in the period of satellite coverage, at time +4.50 to +4.75 hr with satellites 1, 3, and 5 available. The ship proceeds west for 5 min, executes a 360-deg turn at 3 deg/sec, continues west for 10 min, and then turns and steams south for 5 min. Normal sea

conditions exist during the first 10 min followed by 5 min of heavy seas. The dynamics of a container ship were chosen as a representative example for the simulated ship motions (Ref. 7). The Z-set was designed for dynamics far in excess of these; hence, the ship type selected for the simulation does not impact the general applicability of the findings of this study.

6.3.2 Measurement Errors

In addition to the best-guess noise values of the true measurement error models, Table 6-3 lists the initial state uncertainty data and the random measurement errors. The Z-set filter covariance matrix was initialized to the values corresponding to the tangent plane coordinate filter sigmas given in Table 6-3b ; the computations are in earth-centered coordinates with only the display in tangent plane coordinates. The filter state initialization uncertainty data are randomly selected from an error population with normal distribution and zero mean and defined by the true sigmas (standard deviations). The filter model includes process noise on the velocity, clock phase, and frequency states, modeled as random walk processes. The velocity process noise includes maximum as well as nominal values for use with the process noise adaptation feature. The values selected for velocity were determined experimentally for the shipboard application. The filter random measurement errors for pseudo and delta range are given in Table 6-3c.

6.3.3 Summary of Simulation Results

Figures 6-4 and 6-5 summarize the ship simulation activities for two of the many simulation runs performed. The satellite coverage, ship tracks, and sea conditions are as described in Sec. 6.3.1. Representative samples of the simulation

Table 6-3 Filter Measurement Errors and Initialization Data

a) True Measurement Error Model		
Type (Error Sigma)	Range, ft	Delta Range, ft/sec
Bias	14.8	0.0
Scale factor	0.0	0.0
Time correlated	10.6	0.0
White noise	100.0	0.1
Correlation time, sec	20.0	0.0

b) Initial State Uncertainty Data					
Parameters	Time Sigma	Filter Sigma	Max Noise	Nom Noise	Correlation Noise
X position, ft	6000	6000	0	0	0
Y position, ft	6000	6000	0	0	0
Altitude, ft	100	100	0	0	0
X velocity, ft/sec	40	40	20	5	0
Y velocity, ft/sec	40	40	20	5	0
Z velocity, ft/sec	20	20	20	5	0
User clock phase, ft	2000	2000	1	1	0
User clock freq, ft/sec	2	2	0.17	0.1	0

c) Random Measurement Errors		
Variables	Sigma	Startup Sigma
Range, ft	100	1000
Delta range, ft/sec	0.1	10

results are presented as reconstructed computer plots of the ship's horizontal position errors for X (north) and Y (west) and the velocity error for X, all in geographic coordinates. Complete computer printouts of these two simulation runs for all eight filter states, accompanied by printouts of the ship's track location and the amplitude and frequency of the ship's six degrees of motion, are presented in Appendix B.

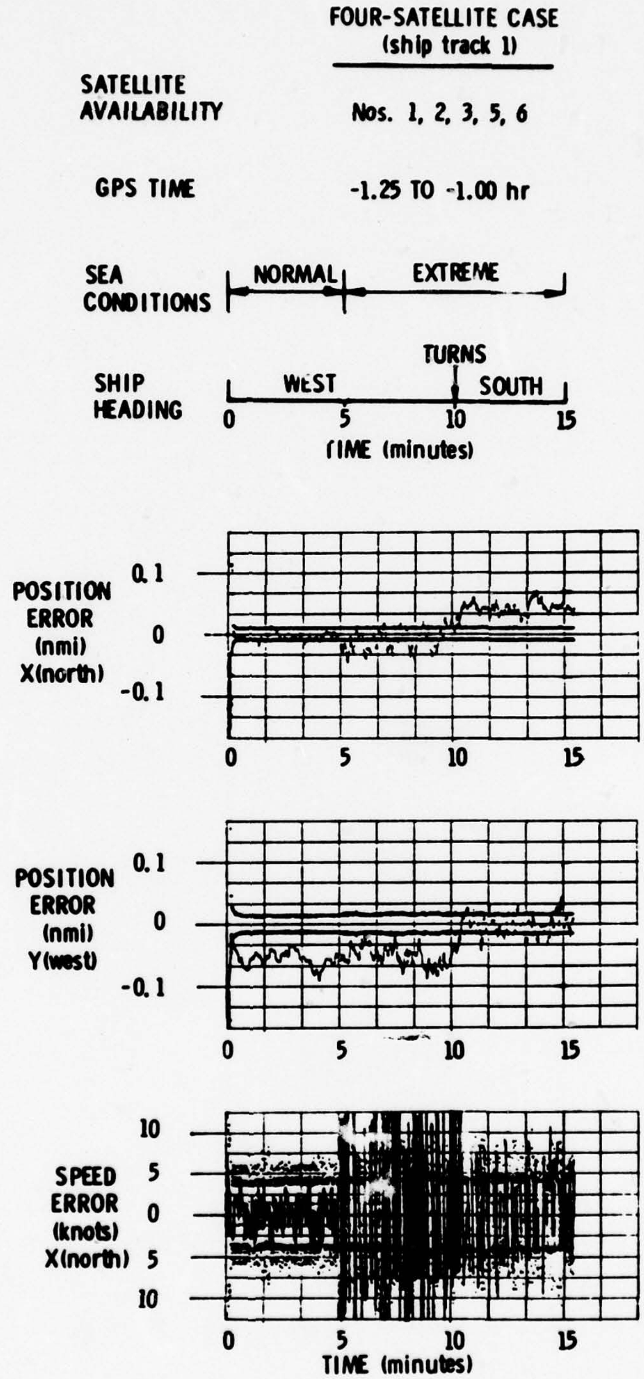

Fig. 6-4. Ship Simulation, Track 1

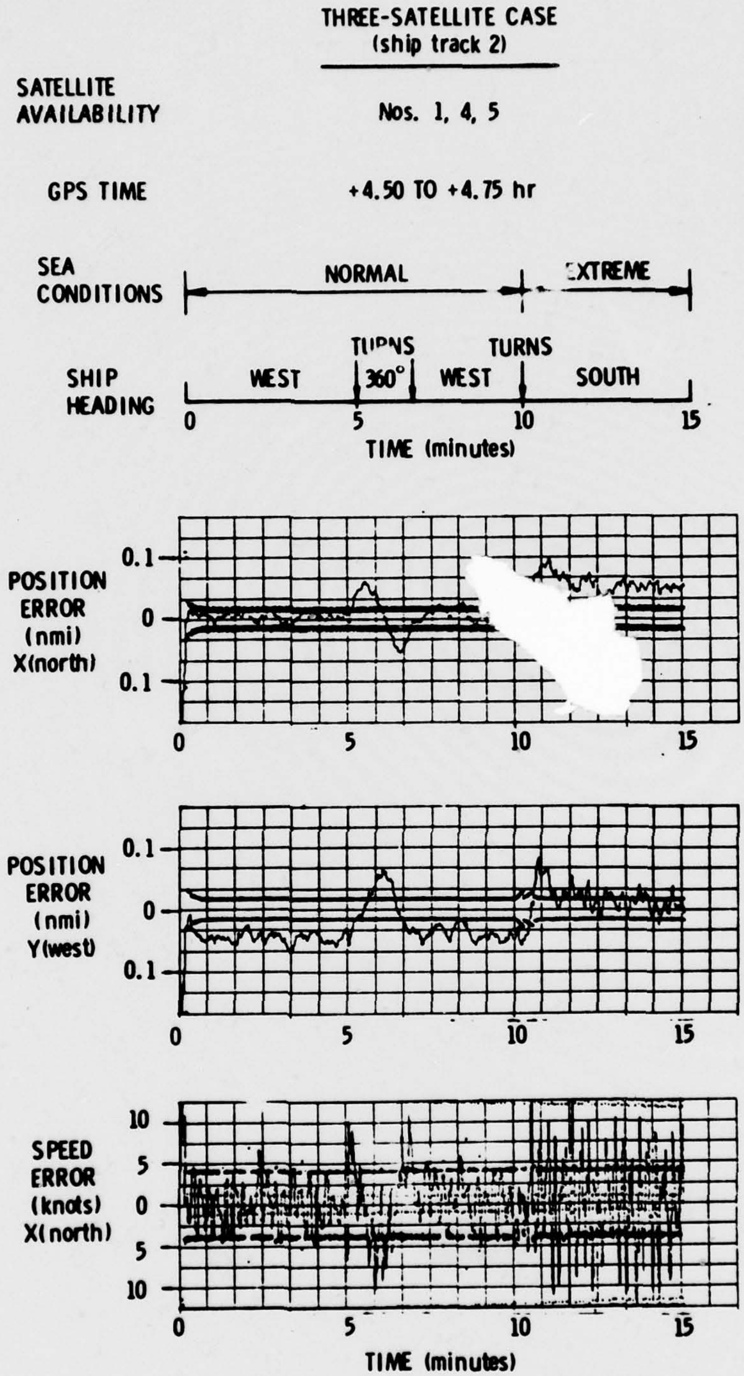

Fig. 6-5 Ship Simulation, Track 2

6.3.3.1 Navigation Performance

The ship's position and speed errors for Track 1 with four satellites in view and for Track 2 with three satellites in view are given in the lower portions of Figs. 6-4 and 6-5, respectively. The position errors are expressed in nautical miles and the speed errors in knots. Also shown on the same plot for each filter state are the ± one-sigma values computed by the filter, which are taken from the filter covariance matrix and represent the filter estimates of the uncertainty in the solution. The steady-state solution for position is frequently outside the ± one-sigma values because the antenna is located 300 ft forward and 100 ft above the ship's center of gravity, which is the reference point for true motion in the ship simulation. A small portion of the position bias also comes from the bias in the measurements. Both the a priori and a posteriori values of the error and the ± one-sigma values are plotted at each measurement time. The separate traces seen in the velocity covariances correspond to the slightly different solutions for the different satellites and are due to the effect of the process noise adaptation introduced in the simulation.

At the start of the simulation runs for the four satellite case at -1.25 hr, the azimuth and elevation angles to the selected satellites for Track 1 are:

Satellite No.	Azimuth, deg	Elevation, deg
1	-166.8	10.4
2	-194.8	50.6
3	69.8	58.1
6	-27.2	43.2

Figure 6-4 shows that the horizontal position errors vary between 100 to 200 ft (about 0.016 to 0.033 nmi, with an

additional 300-ft bias in the position reading due to the antenna's location (at the bow). Since the Z-set has no lever arm correction, the displayed information represents the antenna position. Thus, the Z-set determines position for the ship's bow instead of for its center of gravity. The excellent response of the Z-set to a change in the ship's position may be noted; also, the effects of the heavy seas on the position errors are minimal. The one-minute period of the ±15-deg yaw excursions can be detected as the modulated waveform riding the average position errors. Also apparent are the shorter-period pitch and roll, especially during heavy sea conditions. The amplitude and frequency of the motions for the ship's center of gravity and the antenna are given in Table 6-4.

Table 6-4. Motions of Ship's Center of Gravity and Antenna

Conditions		Roll	Pitch	Yaw	Heave	Surge	Sway
Ship	Sea	±deg/ period, sec	±deg/ period, sec	±deg/ period, sec	±ft/sec/ period, sec	±ft/sec/ period, sec	±ft/sec/ period, sec
Center of Gravity	Nominal	5 / 15	1 / 11	3 / 60	1.14 / 11	1.0 / 11	1.0 / 15
	Extreme	25 / 15	4 / 11	15 / 60	5.7 / 11	2.5 / 11	2.5 / 15
Antenna[a] Velocities[b] ± ft/sec	Nominal	3.7	3.0 (up) 1.0 (fwd-aft)	1.7	1.14	1.0	1.0
	Extreme	18.5	12.0 (up) 4.0 (fwd-aft)	8.5	5.7	2.5	2.5

[a] Z-set antenna location assumed 300 feet forward of and 100 feet above ship's center of gravity.

[b] Values are peaks of simple harmonic motion.

The velocity excursions (Fig. 6-4) along the track when the ship heads west and along the crosstrack when it steams south are between 4 and 17 ft/sec (from about 2.5 to a little more than 10 knots). This is a large fluctuation with respect to the ship's speed of 18 to 20 knots; the display of speed produced would not be very useful. As mentioned previously, the Z-set tracks the ship's antenna, and the ship motions are amplified by the length of the moment arm between the center of the antenna and the ship's center of gravity.

At the start of the simulation run for Track 2 at +4.5 hr, the azimuth and elevation angles to the selected satellites were:

Satellite No.	Azimuth, deg	Elevation, deg
1	61.0	16.7
4	-141.0	44.4
5	-178.5	11.7

For the three-satellite case, a good solution for horizontal position estimates was obtained by constraining altitude through simulated barometric altimeter measurements and zeroing, or fixing, the gain on the altimeter bias state. Subsequent to this simulation effort, and partly as a result of its findings, the Z-set specification was changed to delete the barometric altimeter input option and substitute the manually introduced altitude value during the initialization procedure. This software change provides an altitude hold whenever fewer than four acceptable satellites are in use, effectively implementing the altitude constraint. Position errors vary from 100 to 200 ft for the three-satellite case (Fig. 6-5).

6.3.3.2 Velocity Filters

As a first approach to remove the antenna lever arm effect, an attempt was made to tune the filter with simulated velocity process noise to reduce the noisy velocity display data. Adequate results were obtained by changing the nominal and maximum process velocity noise to 0.05 and 0.2 ft/sec. This made the filter less sensitive to the measurements and reduced the undesirable effects of antenna motion from 20 to 4 ft/sec. However, the Z-set response to the ship's turns and yaw motions became sluggish and produced errors of $\pm$ 12 to 15 ft/sec and $\pm$ 8 ft/sec respectively.

The fact that the unwanted velocity components were periodic, or in any case zero mean, suggested the use of low pass filters. Two types of output velocity filters or smoothers were programmed into the simulation, a first-order digital filter and a velocity box filter. The latter simply constrains velocity changes between samples to less than a preselected value. The equations developed for the two solutions appear in Appendix B, (Fig. B-13).

Good results were obtained with the first-order digital filter using a weighting factor of 0.01. The initial settling time is about 300 sec, with a good response to ship maneuvers. The filtered velocity excursions are limited to $\pm$ 0.5 - 1.0 ft/sec in normal seas, and for heavy sea conditions are about $\pm$ 2 ft/sec. For the velocity box filter, results comparable to the first-order digital filter were obtained, with a constraint velocity change of 0.035 ft/sec; settling time, however, was about 600 sec. Figures B-14 and B-15 present the results obtained for these two velocity smoothers.

Computer printouts of the position and velocity information presented in Fig. 6-4 are included in Appendix B as part of a selected set of printouts illustrating the ship simulation activities.

6.3.3.3 Miscellaneous Checks and Findings

A number of minor checks regarding the Z-set navigation performance for ship use were made, and the results obtained form the basis for the following observations. In the simulation, the Z-set navigation accuracy obtained for pseudo range only almost equals the accuracy obtained from pseudo plus delta range measurements. From an initial 160-nmi position error, the filter convergence to the 100- to 200-ft error level is accomplished in 50 sec. The Z-set clock sensitivity to acceleration, a source of error in avionics applications, introduced no apparent error at a level of 10^{-9}/g (1 ft/sec/g).

7. RECOMMENDATIONS, PHASE II TASKS, AND FUTURE INVESTIGATIONS

This section provides recommendations for the selection of the Z-set antenna, the preamplifier, and the cable that connects the antenna/preamplifier assembly with the receiver/processor. The factors unique to marine applications were studied in detail. The Phase II task description addresses the activities required to conduct the demonstration phase and complete the MARAD/GPS Demonstration Project. During this Phase I study, many aspects of the GPS user equipment showed economic potential for marine application. A significant area for future investigations is discussed.

7.1 RECOMMENDATIONS FOR Z-SET CONFIGURATION

The analysis of the Z-set front-end requirements for the demonstration was directed toward providing hardware selection recommendations for the shipboard antenna, preamplifier, and cable that connects the preamplifier with the receiver. A requirement is that proper Z-set operation be obtained at any ship-to-satellite elevation angle greater than 10 deg for all azimuth angles, and for all ship roll angles up to $\pm$ 25 deg.

Although the Z-set will be installed on one ship in a specific preplanned manner, the ship selection has not yet been made; therefore, the recommendation applies to any cable length up to a maximum of 200 ft. Other considerations, both internal and external to the Z-set receiving system, also influenced the hardware selections. Among these are the receiver dynamic range limitations and the need to operate the system in the presence of strong interference in adjacent frequency bands.

7.1.1 Antenna

Five candidate antennas were evaluated. Four of these were made by Texas Instruments and are identified as volute antennas 1 through 4. The fifth antenna was the one proposed by Magnavox for general Z-set use, as described at the Critical Design Review held on 13 December 1977.

Only Texas Instruments volutes 3 and 4 meet the demonstration requirements, with volute 4 providing marginal performance. An antenna gain and coverage requirement is proposed that would be compatible with volute 3:

Requirement: With the antenna oriented such that its axis of symmetry is vertical, its gain at any azimuth angle and for all elevation angles from -5 to +60 deg shall be at least -5 dBIC. At elevation angles from -15 to -5 deg and from +60 to +90 deg, the gain shall be at least -9 dBIC.

It may be observed that a 50 percent efficient antenna providing *uniform* coverage over the required angular field would have a gain of -1.0 dBIC. In this context, the proposed requirement is modest, and preference should be given to an antenna that exceeds the minimum gain requirement with ample margin. The greater gain provides additional protection against interference.

7.1.2 RF Preamplifier

The preamplifier should have a gain of 50 dB when used in conjunction with the recommended cable. For an installation requiring a cable longer than 160 ft (but not more than 200 ft), this preamplifier should be used in conjunction with an auxiliary 5-dB postamplifier. For an installation requiring a very short cable, supplementary attenuation in the cable path

would provide protection against receiver overload in a high-interference environment.

The preamplifier should include an integral bandpass filter to attenuate out-of-band interference. A variety of maritime, aeronautical, and satellite radio navigation services operate in close frequency proximity to the L_1 center frequency (1575.42 MHz) used by GPS, and it may well be that high interference levels will be experienced if sufficient selectivity is not provided in the front end of the receiving system. The input signal is modulated by a 1.023-Mbps bit stream. A 3-dB bandwidth (about 3.0 MHz) would readily transmit this signal, with adequate margin for frequency tolerances.

The state-of-the-art of gallium arsenide field-effect transistor amplifiers in the frequency band of interest readily permits a 2.5-dB noise figure. While the link margin would permit operation with a somewhat poorer noise figure, no significant cost reduction can be expected from a lower-performance unit; therefore, it is recommended that the 2.5-dB noise figure be specified.

Several manufacturers can supply a preamplifier meeting the requirements. An off-the-shelf unit that meets most of the requirements is made by Avantek, of Santa Clara, California. This unit, Model AM-1660, has a specified minimum gain of 50 dB and a maximum noise figure of 2.5 dB (the typical noise figure is 2.0 dB). It includes an integral bandpass filter that requires retuning from 1539 to 1575 MHz (a factory adjustment prior to shipment). The 3-dB bandwidth of this unit is approximately 14 MHz, which is greater than required but less than the 40-MHz value specified in Table XVII of Specification CID-US-115 (Ref. 2). The narrower bandwidth

would more effectively cope with out-of-band interference. The AM-1660 preamplifier will require a separate power source since it cannot operate with the 12-V, 40-mA source of the Z-set power supply.

7.1.3 Cable Recommendations

The recommended cable type is RG-215/U. This is an armored cable with a single braided shield and a 50-ohm characteristic impedance. Although other cables that offer significantly lower attenuation per unit length are available, the specified preamplifier can compensate adequately for this loss. For a permanent installation, where adequately protected cable raceways are available, armored cable is unnecessary. Should the installation plans include adequate protection for the cable, the unarmored equivalent (RG-213/U) may be substituted.

7.2 PHASE II TASKS

The following tasks define the implementation of the Z-set at-sea demonstration and the MARAD, SAMSO/Aerospace, and integration contractor activities necessary to complete the MARAD/GPS Demonstration Project.

7.2.1 Task 1 - Z-set Procurement and MARAD RFP Support

SAMSO will procure for ship installation the specified Z-set antenna. If required, SAMSO will also purchase the preamplifier specified in this report or its equivalent. In addition, SAMSO will support MARAD in assembling the integration contractor request for proposal (RFP). This support will consist mainly of specification updates and review of the statement of work.

7.2.2 Task 2 - Demonstration Plan and Checkout Procedures

SAMSO/Aerospace will finalize the demonstration plan draft submitted to MARAD during Phase I. In addition to incorporating MARAD's comments, the equipment configuration will be updated to reflect the selected shipboard arrangement; the desired data and data rate will be specified; and tables or curves of the expected daily coverage of the TRANSIT and GPS satellite constellations over the route of interest will be included.

7.2.3 Task 3 - Procurement, Modification, and Preparation of the Demonstration Equipment

The integration contractor will accept delivery from MARAD and will purchase or lease the equipment and associated computer programs necessary for implementing the equipment configuration selected by MARAD for the at-sea demonstration. The integration contractor will also perform the hardware and software modifications required on any of the selected configuration equipment to ensure functional operation as defined in the demonstration plan.

7.2.4 Task 4 - Z-set Modifications and Mockup Preparation

The integration contractor will accept delivery of the shipboard Z-set from SAMSO and will purchase or fabricate any additional cables and power sources necessary to ensure proper operation of the Z-set onboard the selected ship.

The integration contractor shall purchase, modify, or develop, as appropriate, the computer programs necessary to implement the Z-set functions, shipboard display, and demonstration software requirements specified in Secs. 4 and 5. The integration contractor will use the demonstration plan to

develop detailed checkout procedures to ensure correct operation of the shipboard equipment during the at-sea trials. Once the software development and module testing have been accomplished, the complete hardware/software mockup will be laboratory tested prior to installation and checkout of the equipment for the at-sea demonstration.

7.2.5 Task 5 - Installation of Shipboard Equipment

For the demonstration, the integration contractor will install aboard the selected ship all the equipment, cables, and other components identified as part of the demonstration equipment. The integration contractor will perform checkout and calibration of the shipboard equipment as part of readiness tests to ensure that the demonstration hardware and software are operational and that all equipment functions in the manner defined in the demonstration procedures.

7.2.6 Task 6 - At-sea Trials and Data Analyses

SAMSO/Aerospace will perform a quick-look analysis of the data collected during the at-sea trials to determine its validity. SAMSO/Aerospace will submit a preliminary evaluation of the demonstration results. An in-depth reduction and analysis of the data as discussed in Para. 4.3.4 is not considered within the scope of this task.

7.3 FUTURE INVESTIGATIONS

In addition to the planned at-sea Z-set demonstration, much more can be done to develop criteria for the evaluation of GPS potential in marine applications. A significant area that surfaced during the Phase I study is the use of GPS as part of an integrated ship navigator. The navigation information from

GPS and the ship's gyrocompass and log can be combined with the shipboard display to show the ship's actual and dead reckoning courses, estimated time of arrival to waypoints, heading, actual speed, etc.

7.3.1 Integrated Ship Navigator

In the mid-1980's, the operational GPS capabilities of continuous fix and high-accuracy measurements of position and velocity will undoubtedly be combined with the MARISAT communication system to usher in an era of high productivity for U.S. commercial vessels with ship control, automatic position reporting, and precise navigation. The following integrated ship navigator discussion provides a cursory look into one of the GPS potential uses for oceangoing vessels.

Figure 7-1 shows the block diagram of the integrated navigator that will probably be encountered in merchant ship navigation circa 1985. This configuration provides navigation, ship control, and position reporting solely by adding the GPS user equipment to onboard subsystems. This concept uses a marine version of the Z-set, with inputs from the speed log and the ship's gyrocompass to provide a simple integrated ship navigator. The shipboard display performs the normal Z-set control and display functions, and in addition allows the operator to insert changes to the steering commands computed from the updated position coordinates. This gives a semi-automatic ship control that will satisfy the current demand for increased automation of ship operation.

As shown, the system expands the number of Z-set Kalman filter states from eight to ten by including course and speed. The filter thus estimates the compass and speed log errors and provides corrected course and speed information for

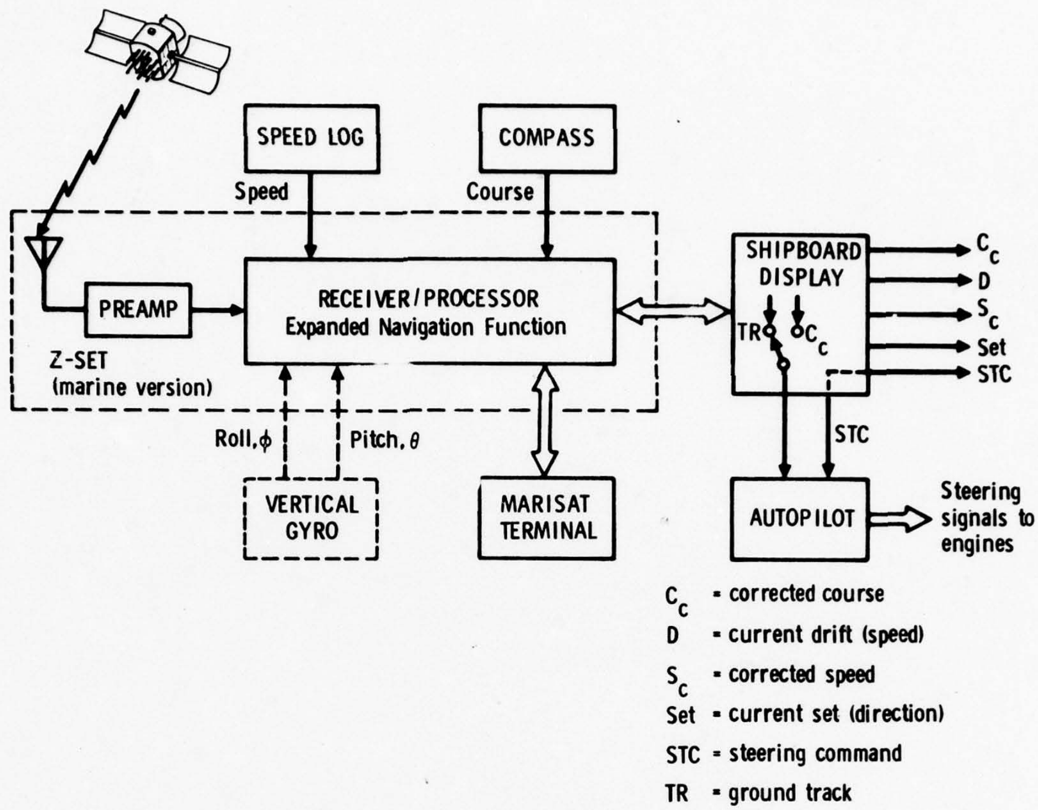

Fig. 7-1. Integrated Ship Navigator

the display. The autopilot can be fed with either corrected course or ground track data for steering purposes. The set and drift of the ocean current also are displayed as the vector difference between the course-speed and the ground track-speed data.

Provision could be made to accept bearings and range measurements to designated landmarks during the highly critical coastal water navigation phases. Fixes by these traditional methods are of accuracy comparable to the Z-set and must be considered mandatory for safe navigation. Because of the need for rapid fix information in pilot waters, it may be desirable

to automate data inputs from the alidade and the radar. The vertical gyro could be added to the navigation system to provide crude vertical reference for removing the Z-set antenna lever arm effect (Sec. 6.3). Note (Fig. 7-1) that the MARISAT terminal directly accesses the modified Z-set and can obtain on command the ship's position, velocity, heading, expected port arrival time, and other desired parameters for automatic transmission to shore.

APPENDIX A

DATA COLLECTION FLOWCHARTS

This appendix presents detailed logic and processing flowcharts for the TRANSIT, LORAN-C, ship attitude reference, and Z-set data collection functions. The following definitions apply to the flags and parameters used in the flowcharts:

<u>TRANSIT (Fig. A-1)</u>

IRPT	A counter to ensure that the TRANSIT data collection flag does not hang up on an I/O problem
IRPTM	Maximum allowable value of IRPT
INFT	Initial entry flag for the TRANSIT data collection function
INT	Input quantity specifying TRANSIT data collection function scheduling
TRNTIM	Time since last TRANSIT data collection
GPSDRK	GPS dead reckoning time: 1 = GPS satellites visible 0 = GPS satellites not visible
T1	TRANSIT data collection interval when GPS satellites are not visible and a TRANSIT pass is not in progress (nominally 30 minutes)
T2	TRANSIT data collection interval when no GPS satellite is visible and a TRANSIT pass is in progress (nominally 10 minutes)
T3	TRANSIT data collection interval when GPS satellites are visible and a TRANSIT pass is in progress (nominally 1 minute)
RTC	Current value of HP 21MX computer real-time clock

LIST	Temporary storage array
ITRAN	Logical device designator for TRANSIT terminal
NTRD	Number of data words transmitted across TRANSIT I/O interface

<u>LORAN-C (Fig. A-2)</u>

LINIT	LORAN-C initialization flag
INTL	LORAN-C scheduling interval
T4	LORAN-C data collection interval
LRAN	LORAN-C logical device identifier
NLWD	Number of words transferred across LORAN-C interface

<u>Ship Attitude Reference (Fig. A-3)</u>

SINIT	SAR initialization flag
INTS	SAR scheduling interval
T5	SAR data collection interval when TRANSIT pass is not in progress (nominally 10 minutes)
T6	SAR data collection interval when TRANSIT pass is in progress (nominally 1 minute)
STRAN	SAR logical device identifier
NSWD	Number of data words transferred across SAR I/O interface

<u>Z-SET (Fig. A-4)</u>

ZINIT	Z-set initialization flag
INTZ	Z-set scheduling interval
T7	Z-set data collection interval when TRANSIT pass is not in progress (nominally 10 minutes)

T8	Z-set data collection interval when TRANSIT pass is in progress (nominally 1 minute)
ZTRAN	Z-set logical device identifier
NZWD	Number of words transferred across Z-set interface

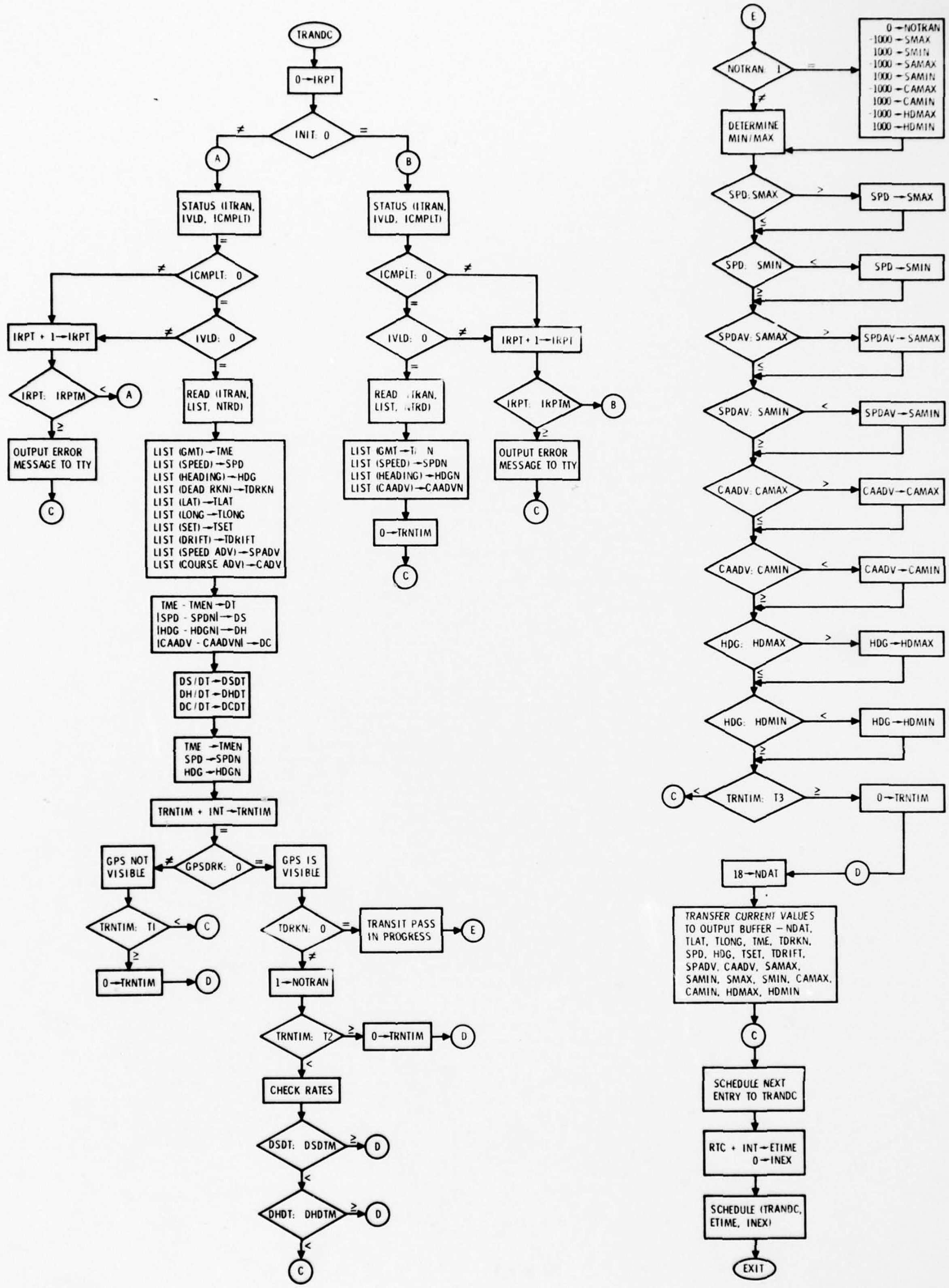

Fig. A-1. TRANSIT Data Collection

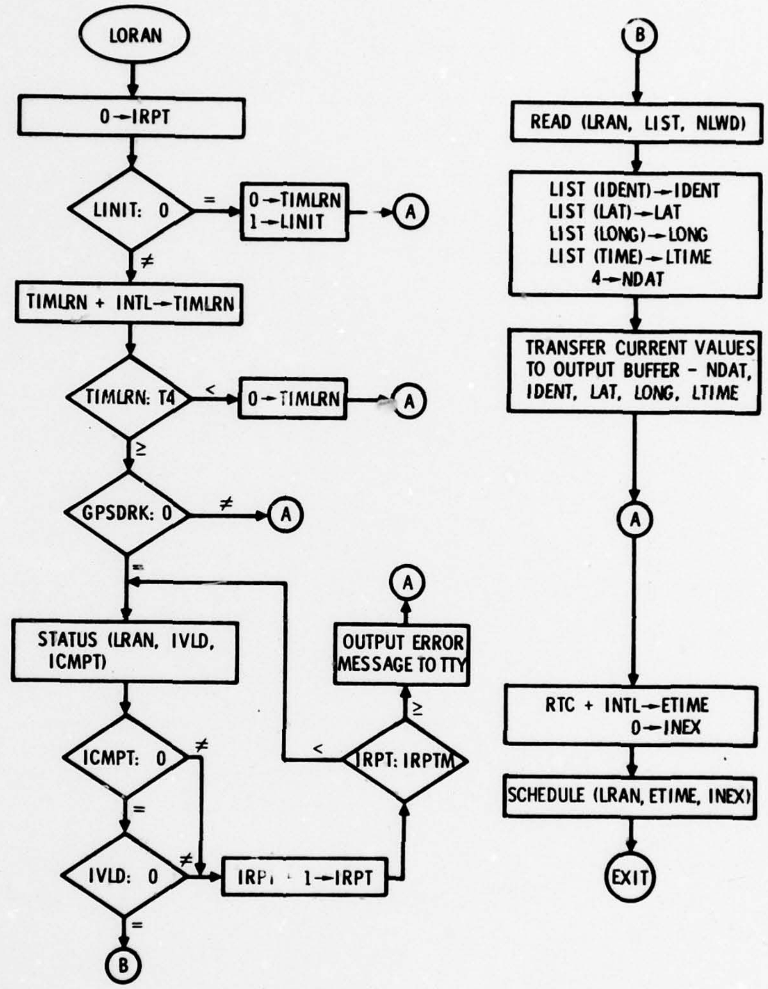

Fig. A-2. LORAN "C" Data Collection

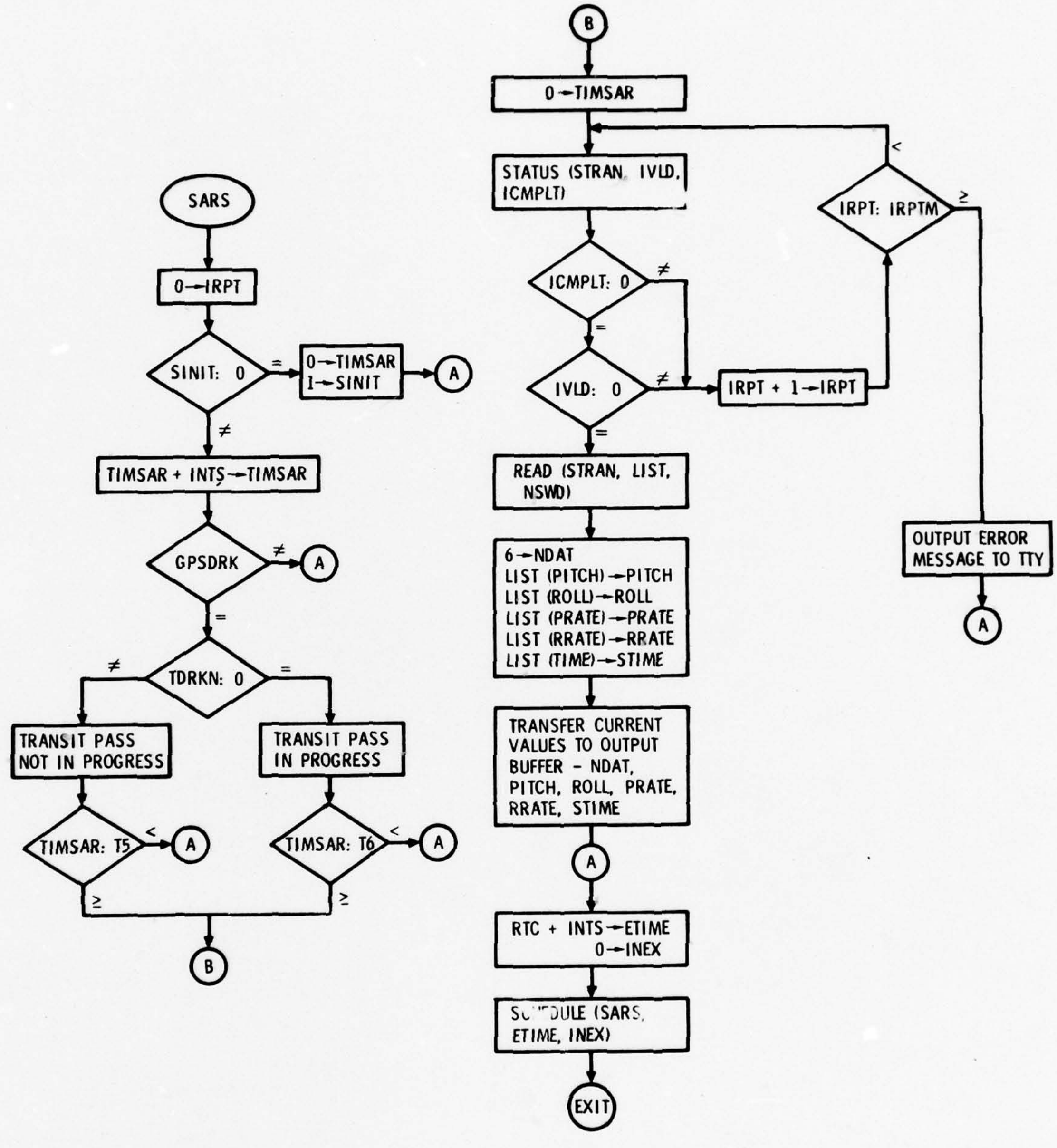

Fig. A-3. Ship Attitude Reference Data Collection

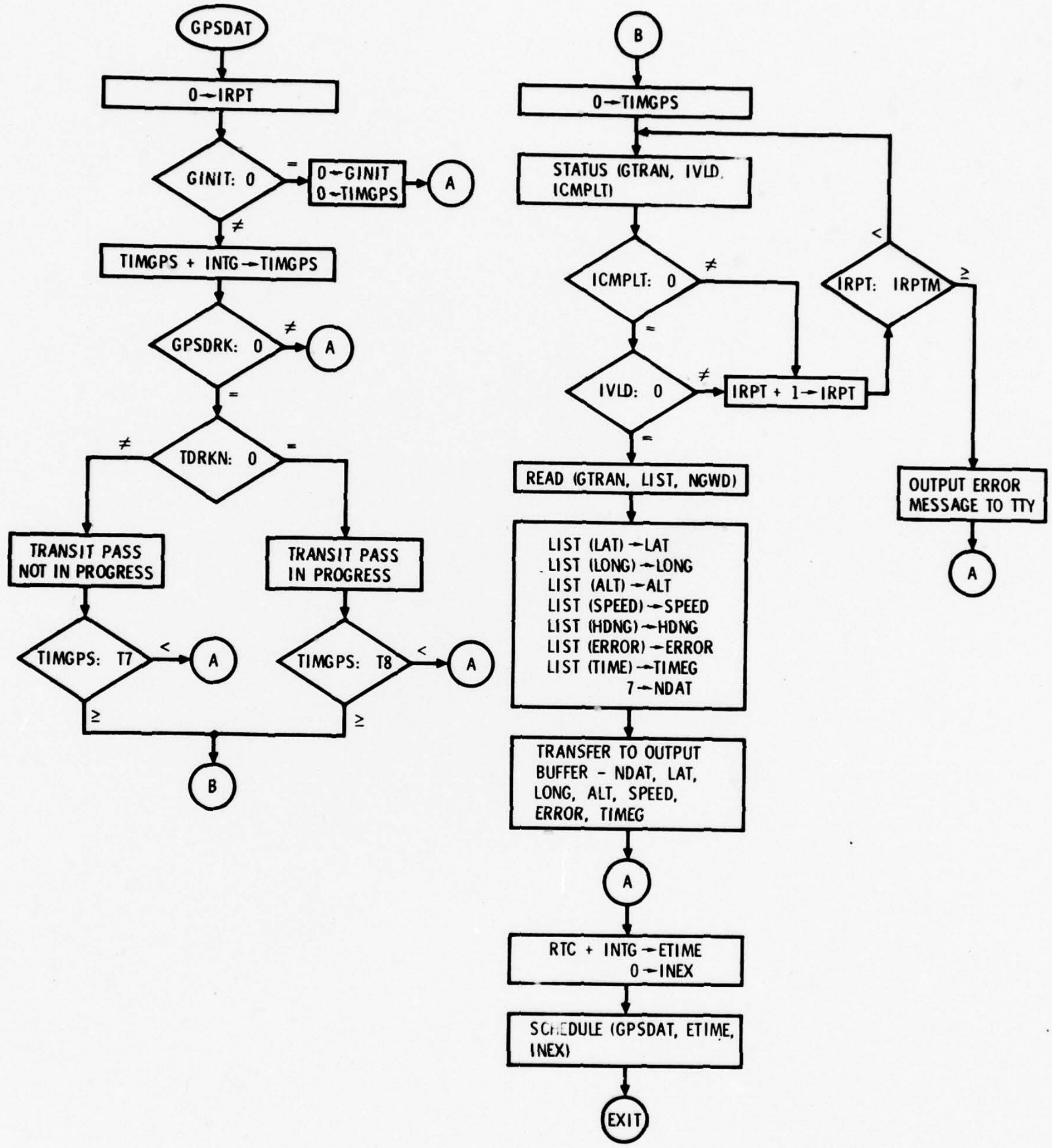

Fig. A-4. Z-Set Data Collection

APPENDIX B

SAMPLE COMPUTER PRINTOUTS OF THE SHIP SIMULATION

This appendix consists of fifteen figures selected from the ship simulation activities. The first six figures, for Track 1, show the track location, ship maneuvers, amplitude and frequency of each of the ship's six degrees of freedom, and the covariance matrix error estimate of the eight-state filter. The next six figures repeat the same information for Track 2. The last three figures show two potential solutions for eliminating the antenna lever arm effect on the velocity data. The labels for the individual plots representing the eight-state filter are defined as:

X POS	=	north position error
Y POS	=	west position error
Z POS	=	vertical position error
X VEL	=	north velocity error
Y VEL	=	west velocity error
Z VEL	=	vertical velocity error
U CLK PH	=	user clock phase error
U CLK FR	=	user clock frequency error

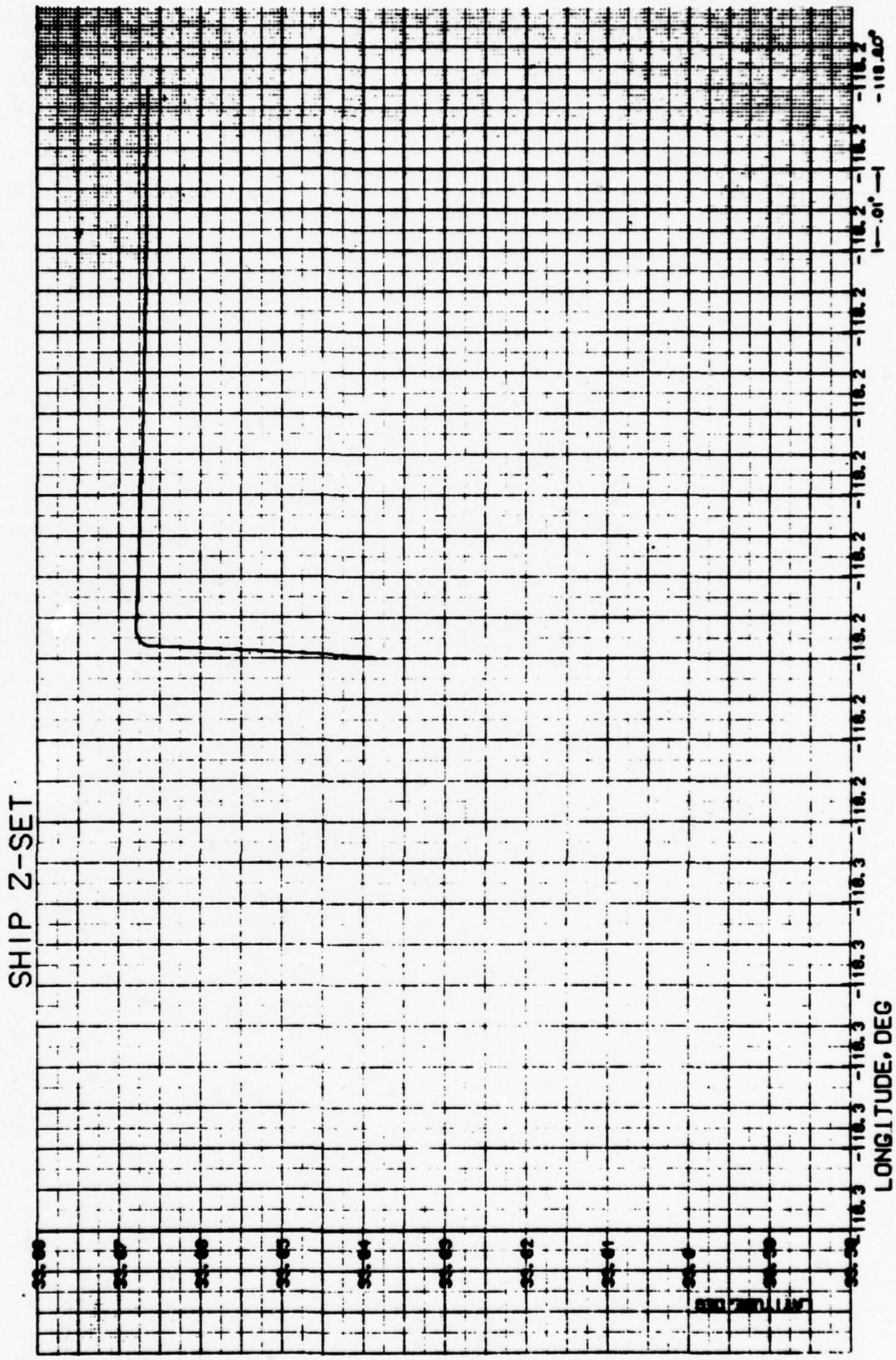

Fig. B-1. Ship Track 1: Location and Heading

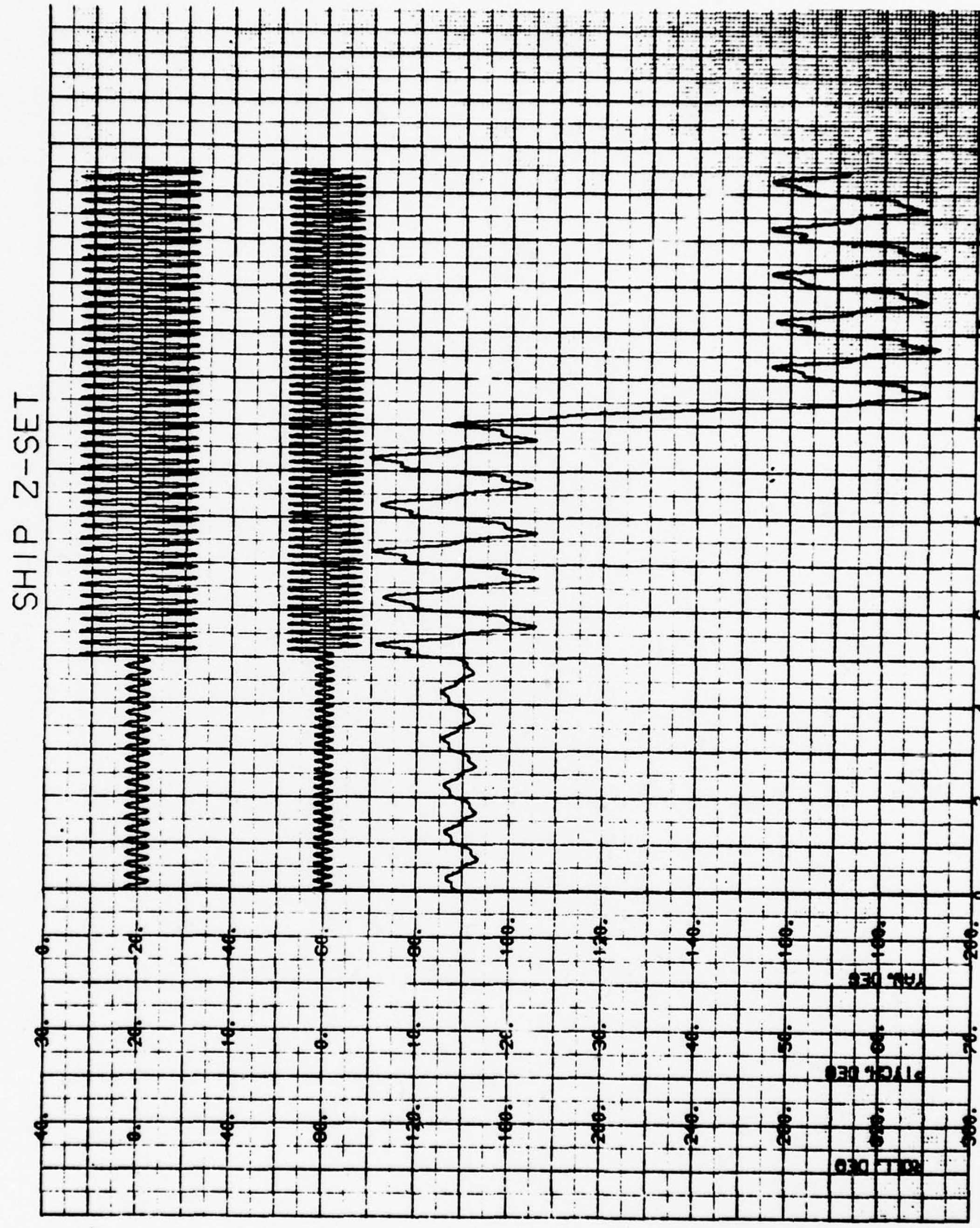

Fig. B-2. Ship Track 1: Roll, Pitch, and Yaw Motions

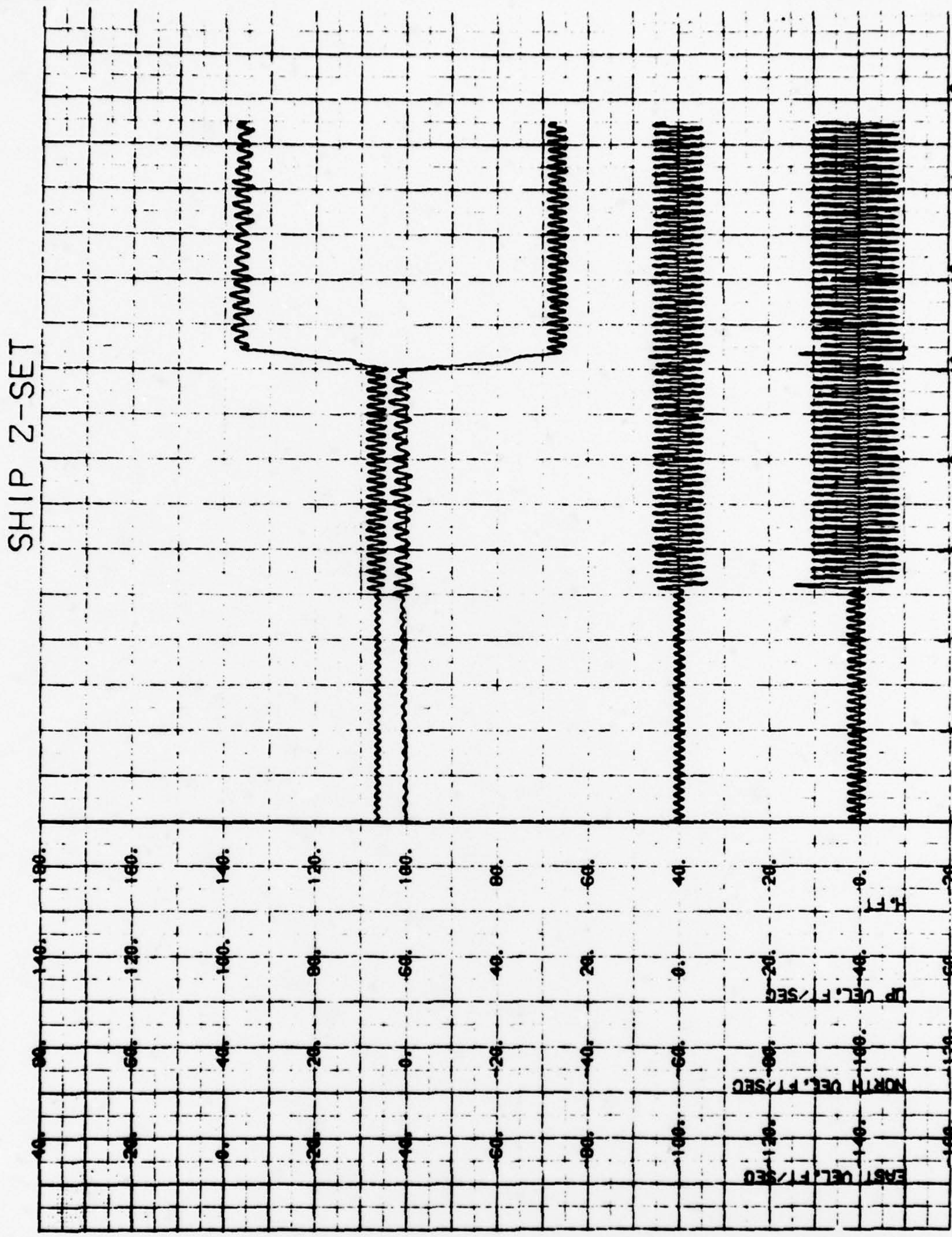

Fig. B-3. Ship Track 1: Heave, Surge, and Sway Motions

MARAD SET Z, RUN D9, 15.5 MIN, 4 SATELLITES, TRAJ. 1

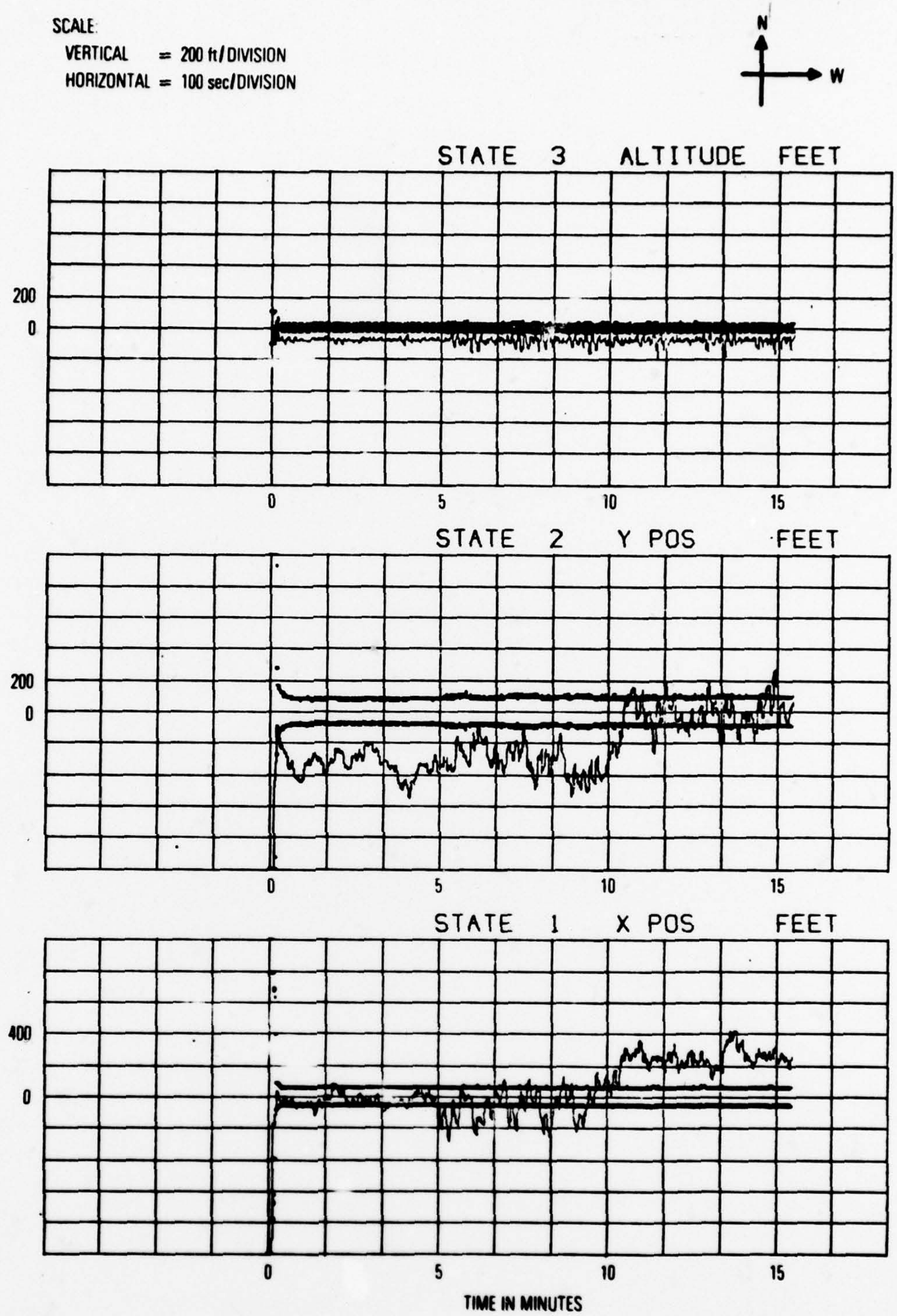

Fig. B-4. Ship Track 1: Position Errors

MARAD SET Z, RUN D9, 15.5 MIN, 4 SATELLITES, TRAJ, 1

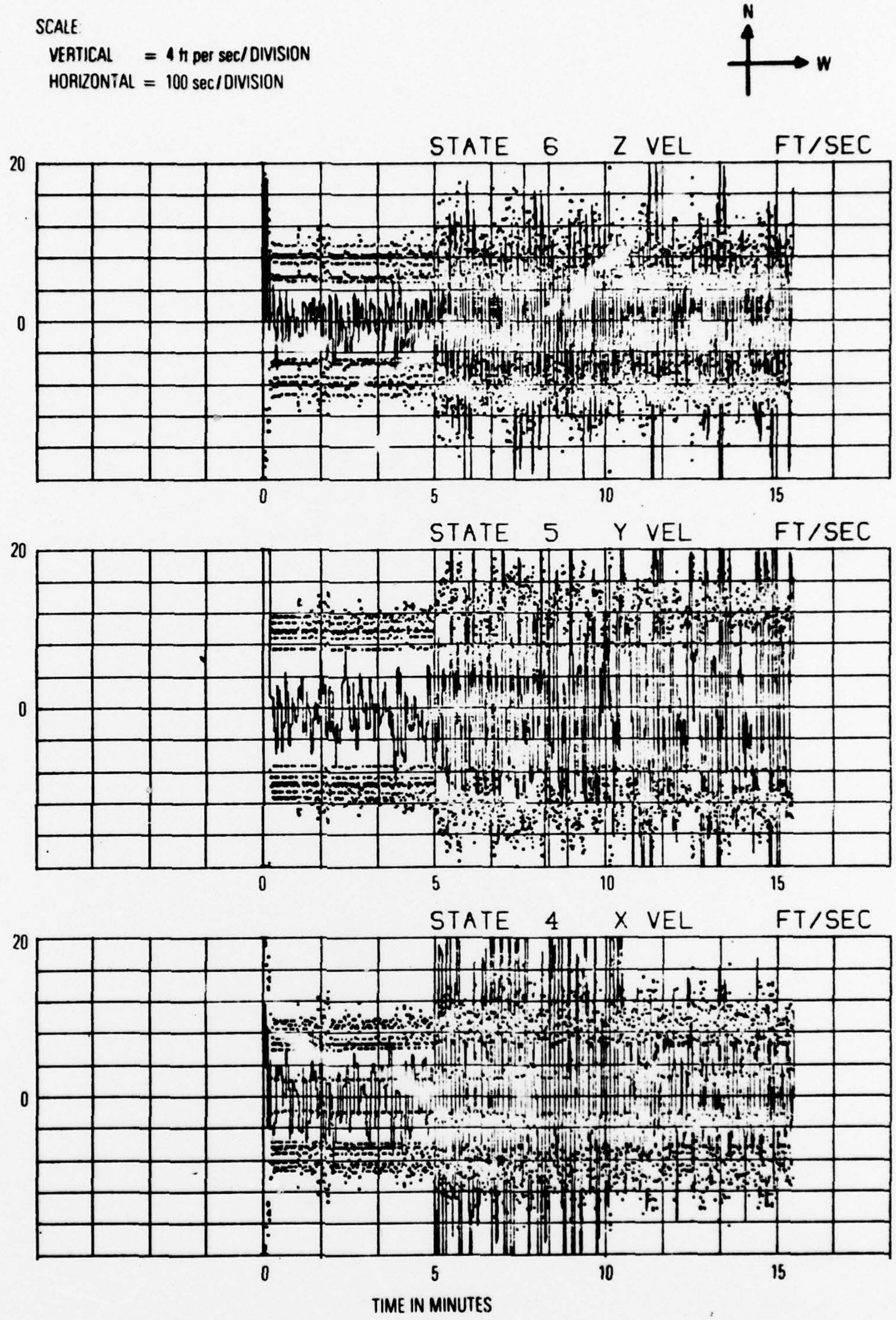

Fig. B-5. Ship Track 1: Velocity Errors

MARAD SET Z, RUN D9, 15.5 MIN, 4 SATELLITES, TRAJ. 1

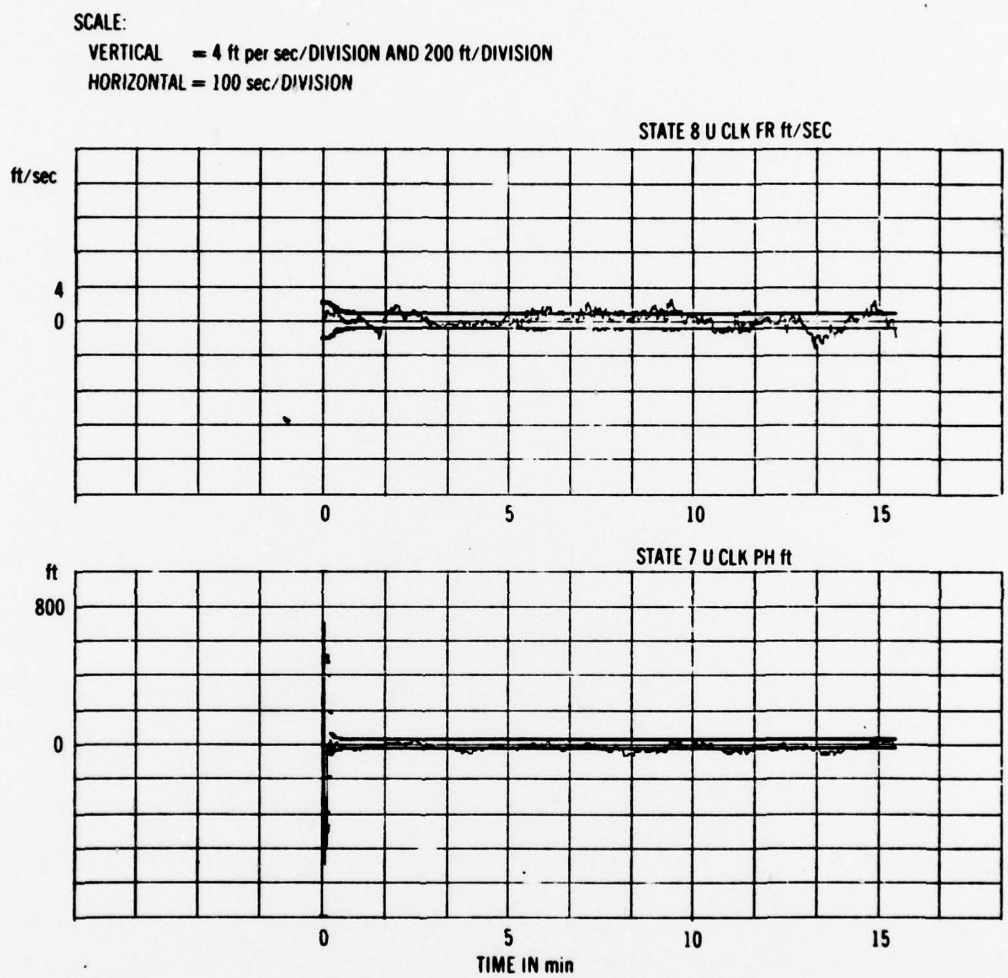

Fig. B-6. Ship Track 1: Z-set Clock Phase and Frequency Errors

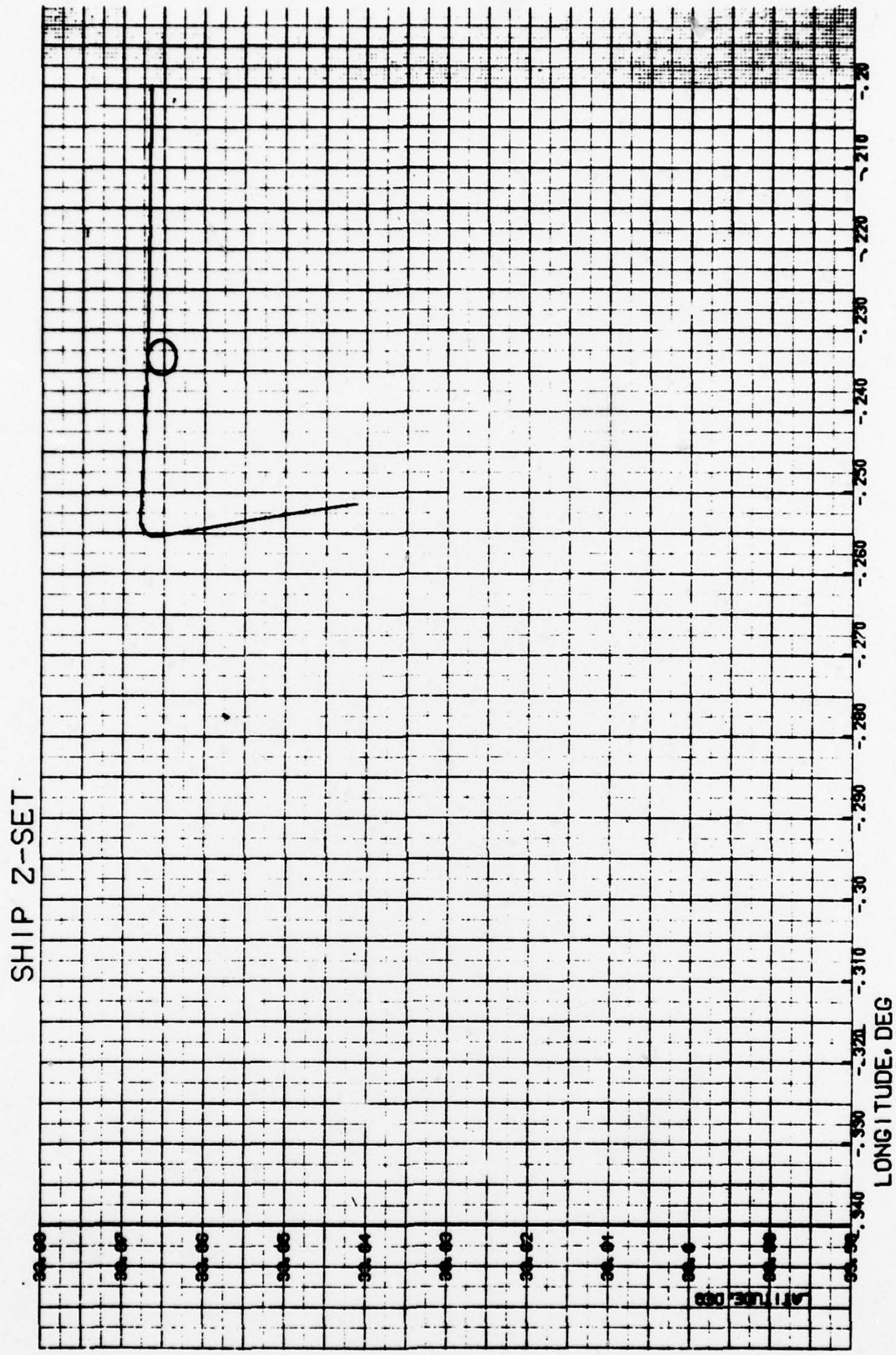

Fig. B-7. Ship Track 2: Location and Heading

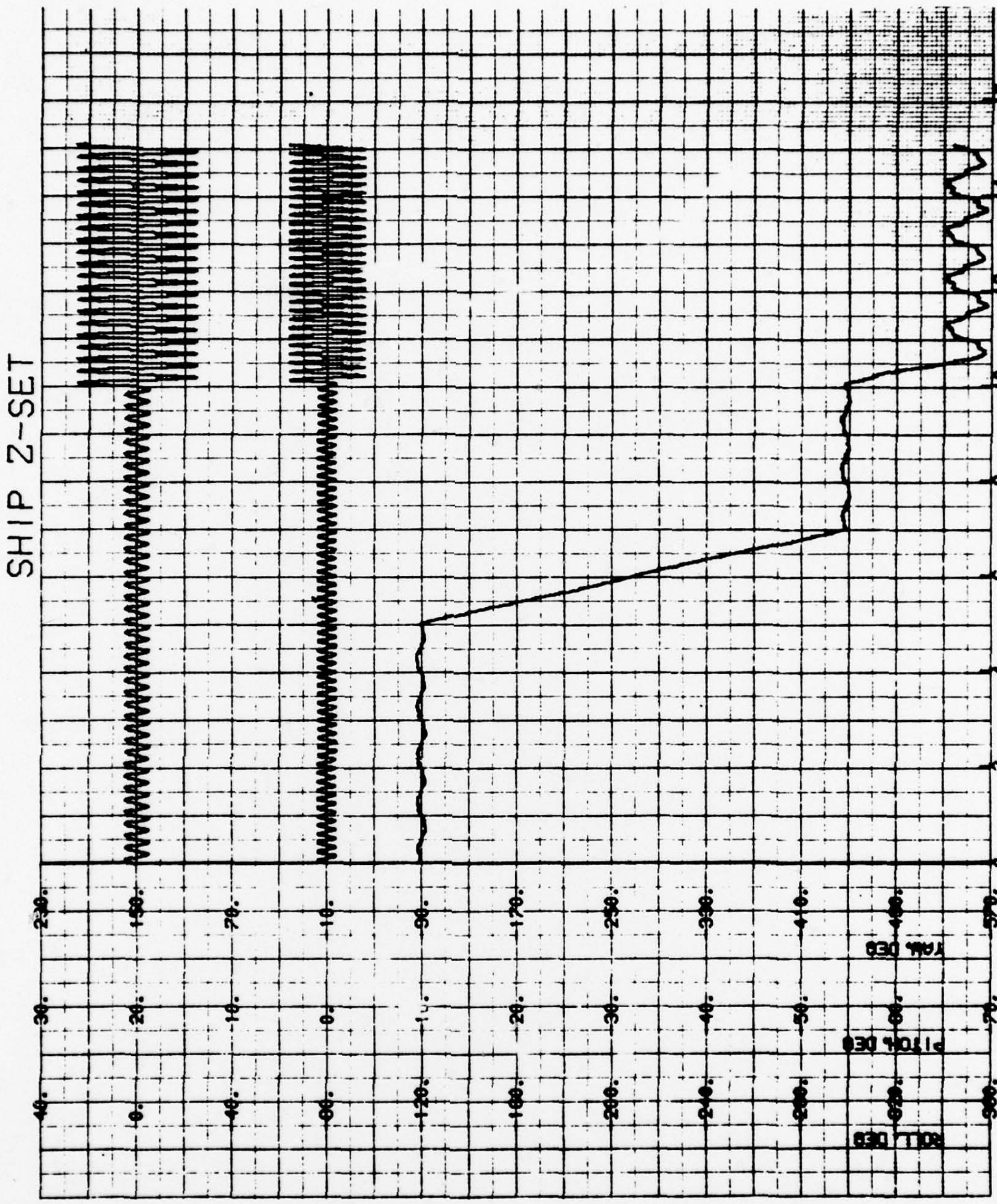

Fig. B-8. Ship Track 2: Roll, Pitch, and Yaw Motions

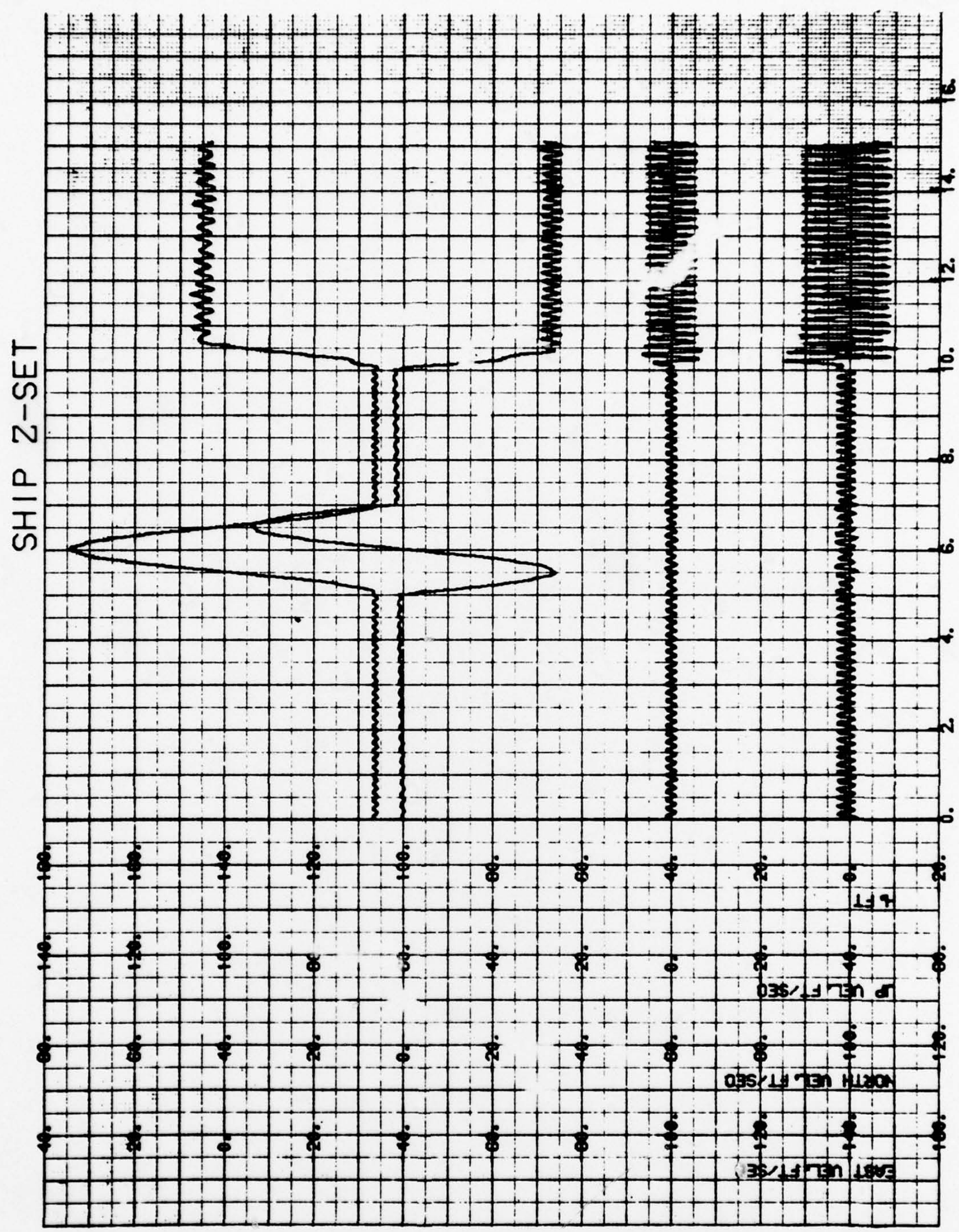

Fig. B-9. Ship Track 2: Heave, Surge, and Sway Motions

MARAD SET Z, RUN A14, 15.0 MIN, 3 SATELLITES, TRAJ. 2

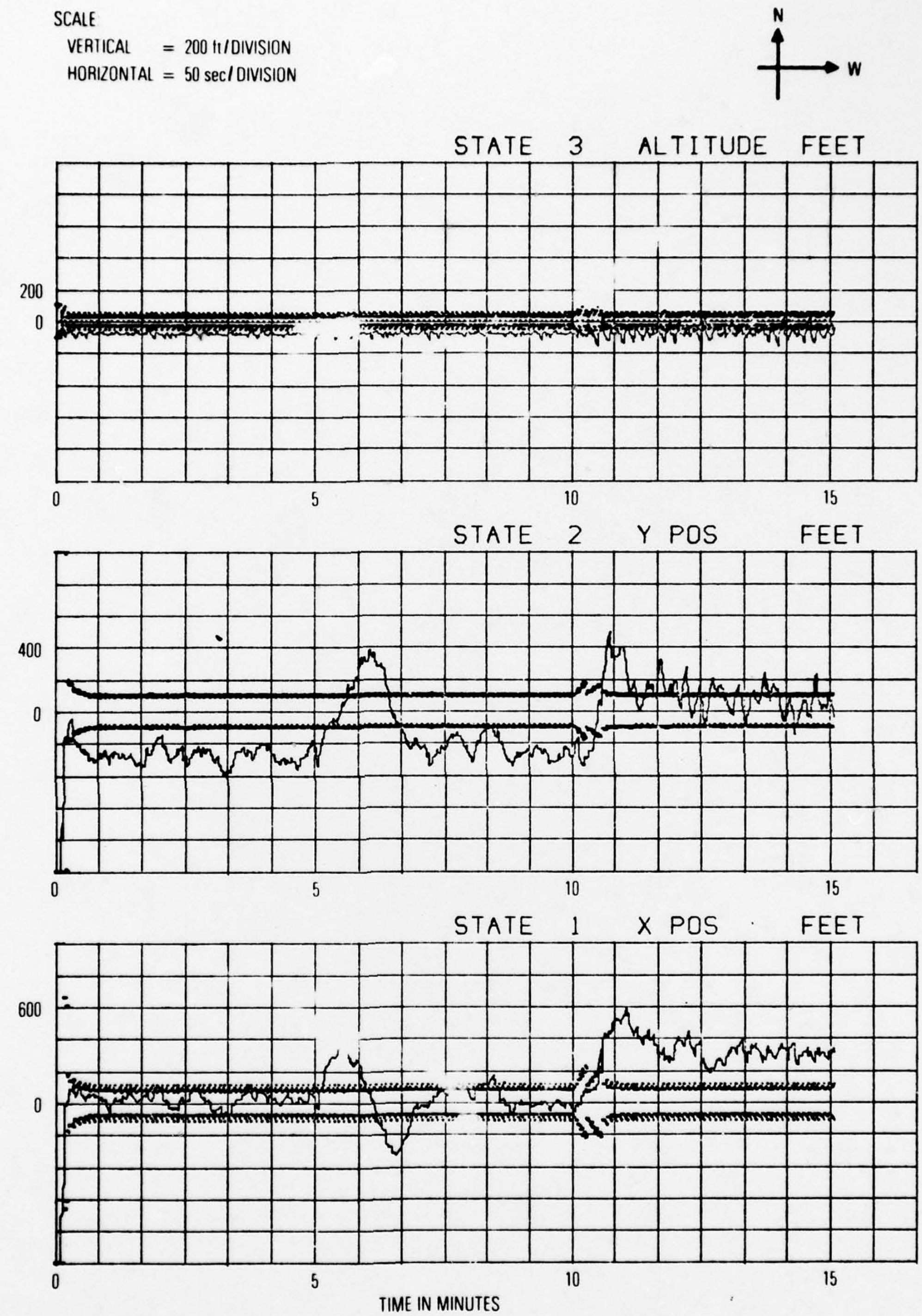

Fig. B-10. Ship Track 2: Position Errors

MARAD SET Z, RUN A14, 15.0 MIN, 3 SATELLITES, TRAJ. 2

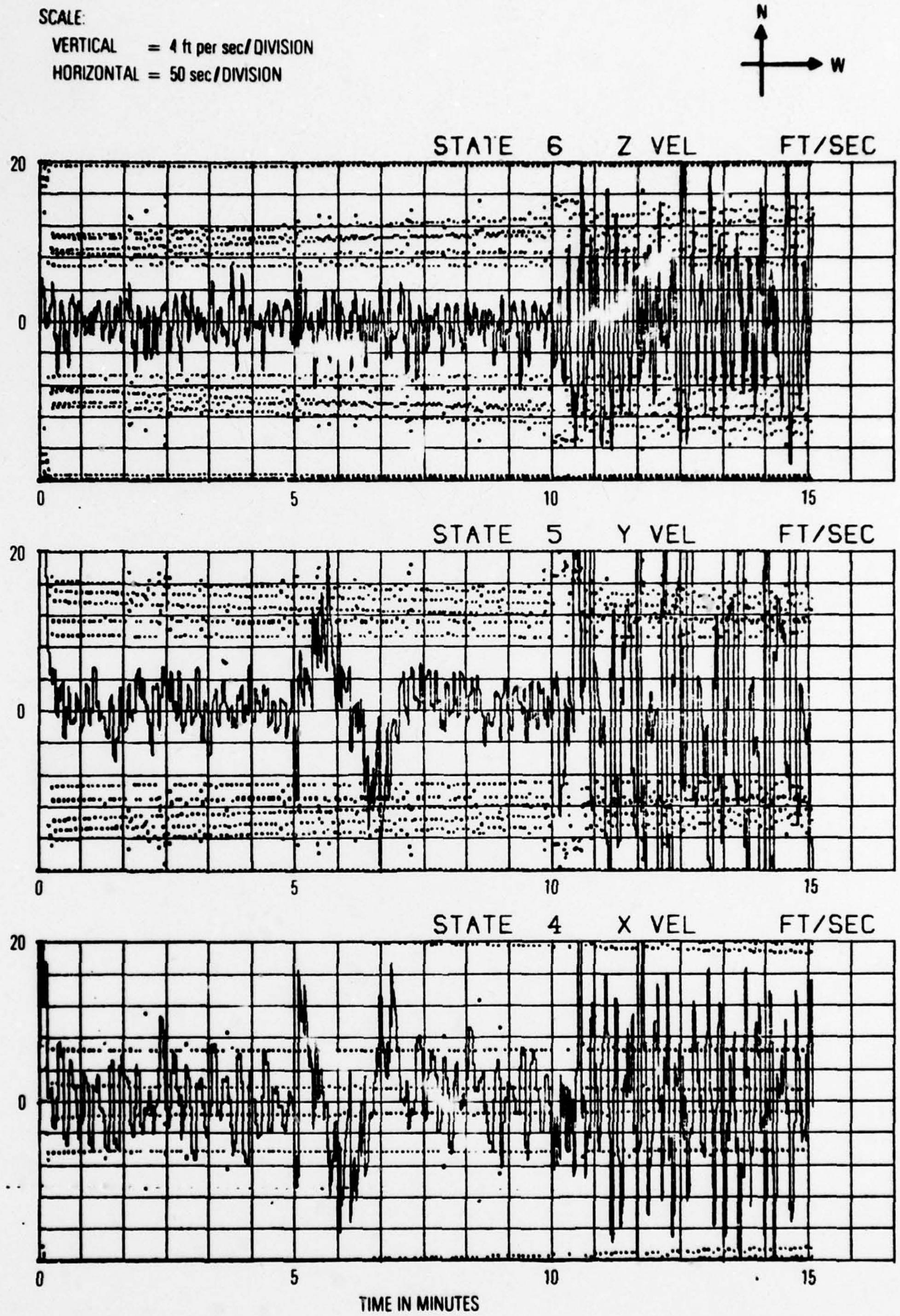

Fig. B-11. Ship Track 2: Velocity Errors

MARAD SET Z, RUN A14, 15.0 MIN, 3 SATELLITES, TRAJ. 2

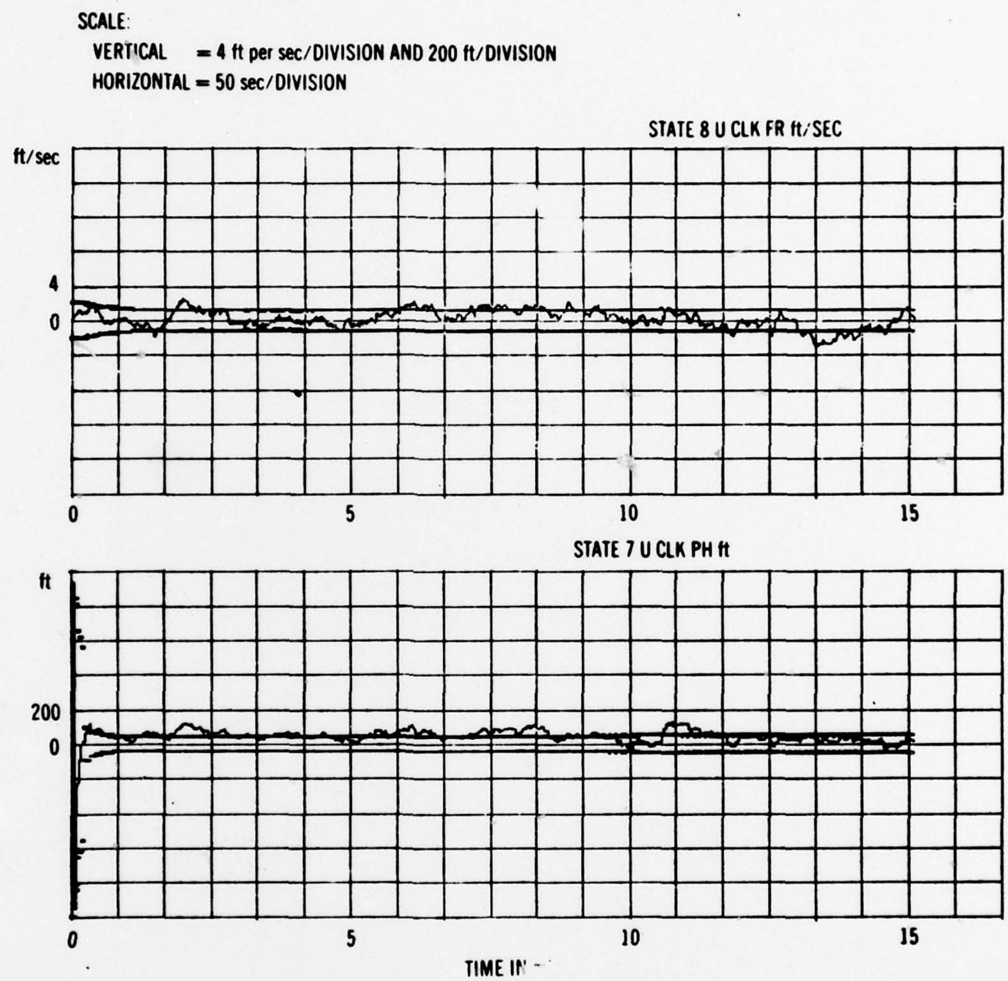

Fig. B-12. Ship Track 2: Z-set Clock Phase and Frequency Errors

Digital Filter

$$C_t = C_{t-1}(1 - W) + W R_t$$

where

C = filtered velocity (Earth centered coordinates, prior to conversion to ground speed and track)

R = Z-set estimated velocity components in Earth-centered coordinates

W = weighting factor $|W| \le 1.0$

$C_1 = R_1$ (initial value)

Velocity Box Filter

$$C_t = \begin{cases} R_t & \text{if } C_{t-1} - \Delta V \le R_t \le C_{t-1} + \Delta V \\ C_t + \Delta V & \text{if } R_t > C_t + \Delta V \\ C_t - \Delta V & \text{if } R_t < C_t - \Delta V \end{cases}$$

where

ΔV = limiting velocity change per measurement cycle

$C_1 = R_1$ (initial value)

Fig. B-13. Velocity Filters

MARAD SET Z, RUN A14A, 15.0 MIN, 3 SATELLITES, TRAJ. 2

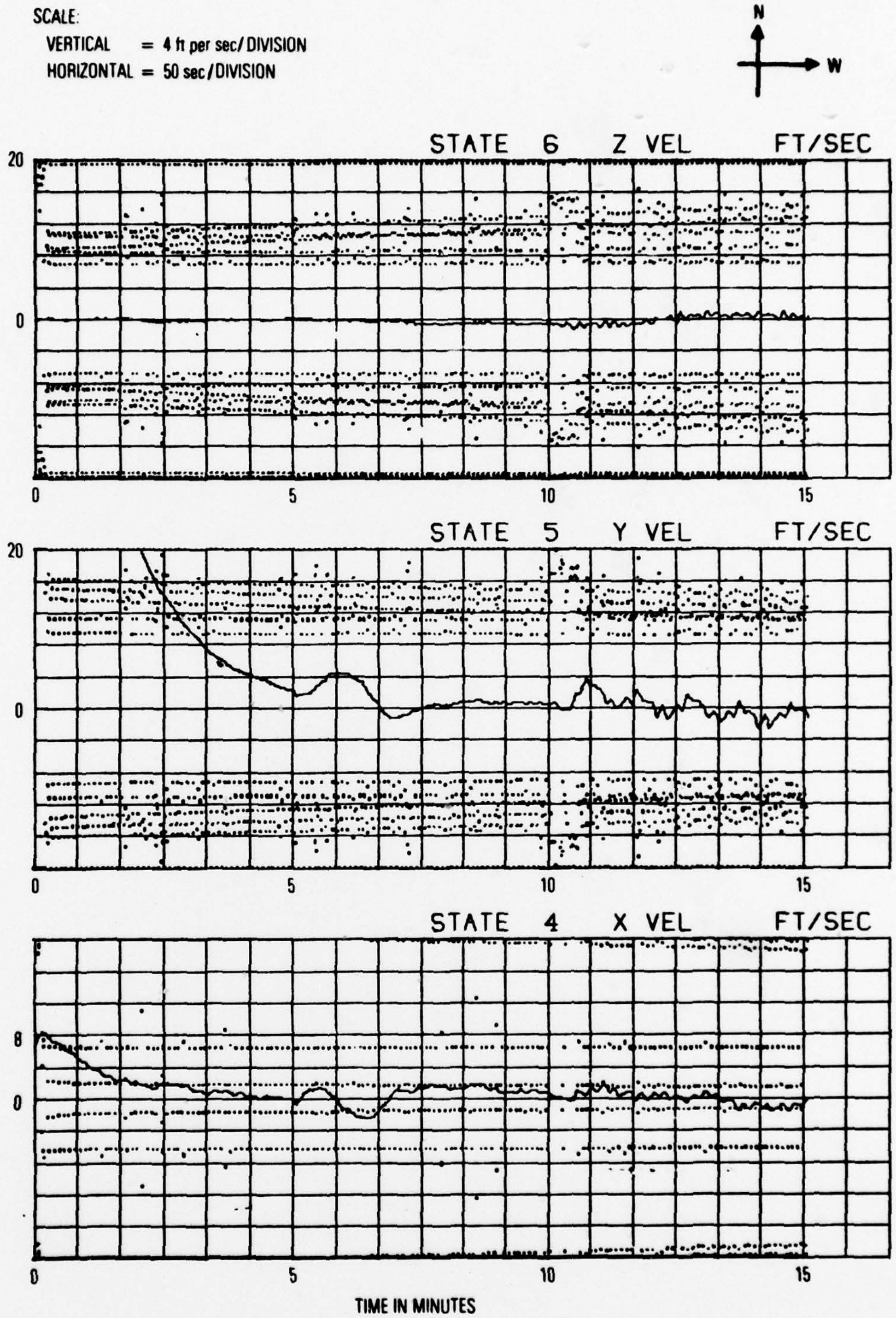

Fig. B-14. Z-set Velocity Readings After Digital Filtering

MARAD SET Z, RUN A14E, 15.0 MIN, 3 SATELLITES, TRAJ. 2

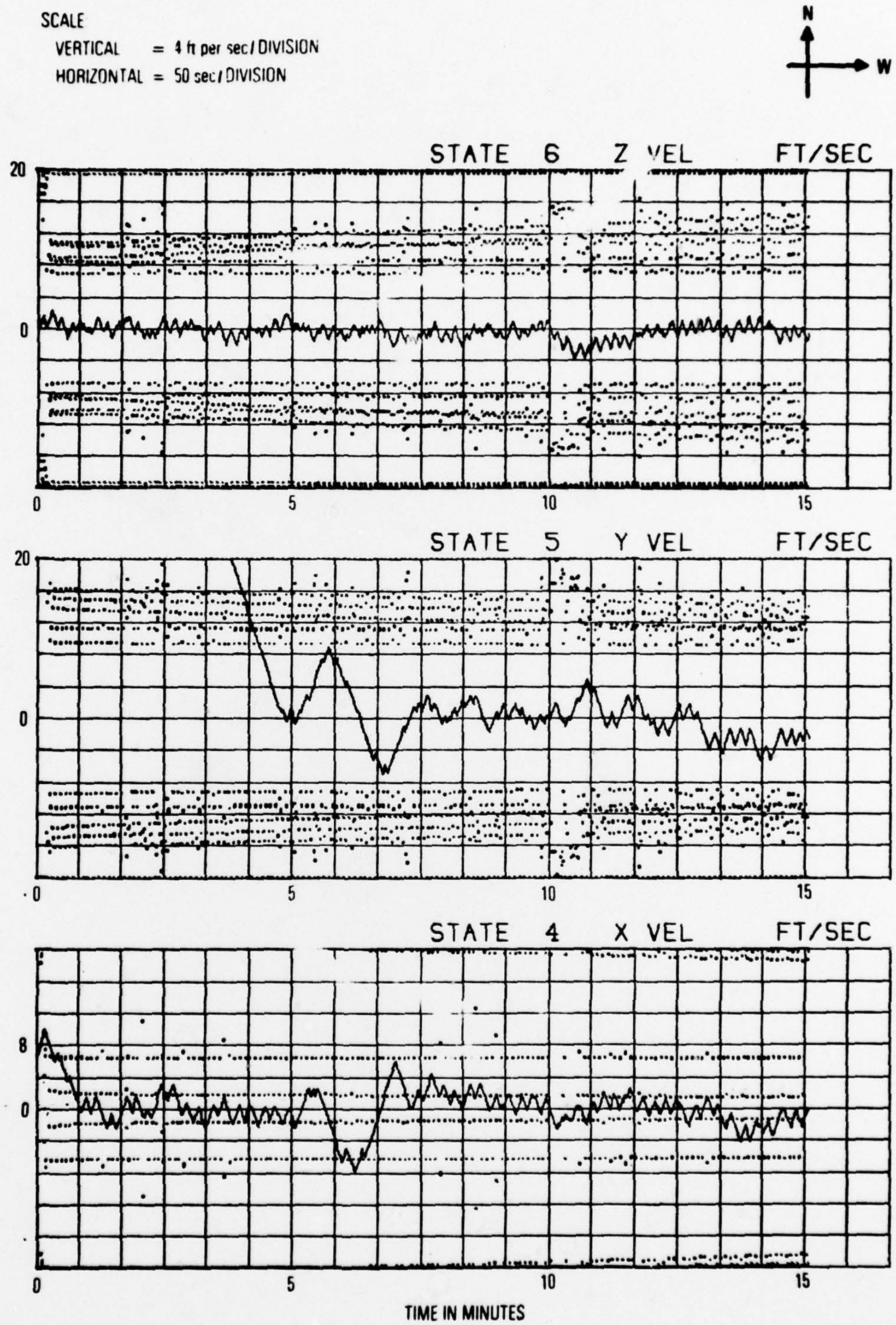

Fig. B-15. Z-set Velocity Readings After <u>Velocity</u> <u>Box</u> Filtering

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